ETIOLOGY OF SUGAR MAPLE DECLINE AT SELECTED SITES IN ONTARIO (1984-1990)

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Report Prepared By:

Phytotoxicology Section
Air Resources Branch
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Report No.
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Principal Investigator/Author: D.L. McLaughlin
Contributing Scientists:
D.E. Corrigan
W.D. McIlveen

1.0 Executive Summary

Forest decline has become a leading environmental issue. In Ontario, concern regarding forest decline has centred on sugar maple. In 1984 the Ontario Ministry of the Environment (MOE) initiated a study to determine the etiology (causal factors) of sugar maple decline in Ontario and to assess the role of atmospheric pollutants in relation to the forest decline phenomenon. Eleven study plots were established (one in Thunder Bay, eight in Muskoka, and two in the Peterborough area) and tree condition was monitored annually from 1984 to 1990. The roots, foliage and soil from symptomatic trees were chemically examined for evidence of inorganic deficiencies or toxicity. Entomological and pathological surveys were conducted, and the history of woodlot management was reviewed for each study site. Annual incremental growth patterns of selected trees were also examined at each study plot.

Provincial Hardwood Forest Health surveys conducted by the MOE in conjunction with this study confirmed that in the mid 1980s sugar maple decline was a scattered, isolated phenomenon in Ontario, although regional patterns were apparent. Generally, in 1986 tree condition was poorest on the shallow, poorly-buffered soil of the Precambrian Shield. Tree condition was consistently better on the finer-textured, deep, and well-buffered soil in the southeast and southwest sections of the province. Tree condition deteriorated marginally in 1987 but improved considerably at most sites by the 1990 survey. This temporal tree condition pattern was also evident at the 11 etiology study sites.

The soil at all eight of the Muskoka area study sites was rated as sensitive to acidification. Mean cation exchange capacity ranged from 0.79 to 1.98 meq/100 g and mean plant-available Al levels ranged from 12 to 28 ppm. There was no relation between tree condition and stand stocking, basal area, total plot biomass, aspect, topography or soil physical characteristics. There was a tendency towards poorer tree condition on poorer sites and with older trees that had accumulated defects.

Tree decline in Muskoka and Peterborough is not likely associated with soil nutrient deficiencies, although the Thunder Bay site may be inherently deficient in Ca, N, P and Mn. However, the foliar analyses revealed that declining trees in Muskoka consistently had lower P and K levels, tree decline in Peterborough was associated with lower Ca and Zn foliar concentrations, and foliage from declining trees in Thunder Bay was S deficient. Fine root Al concentrations averaged 63% higher in declining trees in Muskoka (3800 ppm/declining vs. 2300 ppm/healthy). Root Al concentrations were only marginally lower in declining trees from Peterborough and Thunder Bay compared to healthy trees at these sites. Elevated soil available Al interferes with root P uptake and metabolism. Declining trees in Muskoka consistently had the lowest root P/Al ratio. The possibility cannot be dismissed that Al toxicity, because of soil acidification, is at least exacerbating tree decline in Muskoka.

In the last 20 years there has been a dramatic increase in the number of climate stress events in all three study regions. Climate stress has occurred concurrently with severe forest tent caterpillar defoliation in Muskoka, directly inciting sugar maple decline in this region. Climate stress, in combination with poor site and inefficient woodlot management, has incited tree decline at the one Peterborough site where decline is evident. Climate stress and defoliation have significantly and chronically suppressed tree vigour, thereby providing an opportunity for the root rot fungus *Armillaria mellea* to aggressively invade tree roots and contribute to tree decline.

Examination of annual incremental tree growth showed conclusively that the tree decline observed in the Muskoka region in the early 1980s was initiated by tent caterpillar defoliation in the late 1970s. In addition, the dendrochronological data revealed that a sustained growth reduction has occurred concurrently with increasing atmospheric pollution levels, and the reductions in growth are proportionate with the regional pollution gradient.

In the last 10 to 15 years the forest ecosystem has been stretched virtually to the limit of it's elasticity by an unprecedented frequency of natural stress events that have initiated or prolonged pockets of tree decline on sensitive sites. Atmospheric pollution is an additional stress that the forest must endure and is therefore unquestionably a contributing factor to forest decline in Ontario, particularly in the acid-sensitive Precambrian shield areas of Muskoka.

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5.0 Introduction

Forest decline has become a leading environmental issue. In the last few years articles on forest decline and the possible relationships with atmospheric pollutants have been featured in many popular magazines, most national newspapers, the electronic media, and literally hundreds of scientific publications. In spite of, or perhaps because of the extensive coverage, forest decline remains a contentious and enigmatic phenomenon.

In Ontario, concern regarding forest decline has centred on the effects on sugar maple. In 1984, the Acidic Precipitation in Ontario Study (APIOS) office formed a multidisciplinary research team to conduct an etiological study of sugar maple decline at selected sites. The study team was composed of scientists from the Ontario Ministry of the Environment (MOE), Air Resources Branch, Phytotoxicology Section. The principal investigator was Mr. D. McLaughlin. Contributing scientists were Dr. W. McIlveen and Ms. D. Corrigan. Regional logistical support was provided by Mr. J. Negusanti, Mr. D. Racette and Dr. D. Griffin. Administrative direction was provided by Dr. S. Linzon and Mr. R. Pearson. The investigative team consulted with other researchers and scientists in the Ministry of Natural Resources (MNR), the Ministry of Agriculture and Food (OMAF), and members of the Ontario Maple Syrup Producers Association (OMSPA).

Some facets of the study initiated in 1984 are ongoing. The MOE is committed to continued research into the relationship between atmospheric pollutants and the terrestrial environment. However, the objectives established for the etiological study in 1984 have been addressed and the work completed in 1990. This document is the final report of that study. Because of the large amount of data generated by the study, particularly chemical analysis and tree growth data, extensive use has been made of summary tables. Only significant findings are discussed in detail in the text.

6.0 Objectives

This study had two objectives. The first objective was to determine the etiology (the causal factors) of sugar maple decline at selected sites in Ontario. The second objective was to assess the role of atmospheric pollutants in the current sugar maple decline episode. These objectives were accomplished through an intensive study effort at 11 woodlots from three different regions in the province.

It was also realized that despite the cause of sugar maple decline, there is a demand by woodlot owners for remedial actions designed to mitigate the effects of an impending decline and perhaps rejuvenate a declining stand. Section 11 of this report contains practical suggestions to improve stand vigour. The suggestions are based on the premise that healthy trees are more resistant to environmental stress.

7.0 Background

7.1 Maple Decline: A Complex Phenomenon

7.1.2 Symptomatology

The terms maple decline and maple dieback have been used interchangeably in the popular media to describe the current sugar maple problems encountered in the eastern hardwood forests.

The foliar symptoms most often observed in declining sugar maple stands include abnormally small and pale green (chlorotic) foliage, premature fall colouration, late spring bud flush and early leaf abscission. Researchers in Quebec have observed that trees with wrinkled leaves subsequently develop other decline symptoms.[42] This symptom has not commonly been observed in Ontario. However, it may be useful as an early warning indicator of impending decline in sugar maple.

Subsequent to the appearance of foliar symptoms, progressive crown dieback occurs that usually starts with the fine twigs at the top and sides of the crown and works inwards until whole branches are dead. Tap hole and other superficial wounds heal more slowly, if at all, and bark often sloughs off recently dead branches. Epicormic sprouting on the main bole and at the base of large branches is also frequently observed.

Less obvious symptoms include a reduction of shoot growth and a decrease in fine root biomass. These effects result in a depletion of stored starch reserves, a reduction in annual incremental growth and significant loss of tree vigour. Mortality may occur within a few growing seasons, although recovery of affected trees has been observed. Some recent reports claim that the wood of sugar maple trees that have died suddenly from maple decline deteriorates very quickly and is often unusable. This a controversial symptom that does not appear to be a concern in Ontario. Several thousand ha of dead sugar maple were commercially salvaged subsequent to extensive maple mortality in the Parry Sound area in 1977.[46]

7.1.2 The Decline Cycle

Maple Decline is not the result of a simplistic mechanism. Decline is a complex phenomenon involving many biotic and abiotic factors acting concurrently, sequentially, synergistically or cumulatively to impose stress on the forest ecosystem. Trees require sunlight, oxygen, carbon dioxide, water and several essential inorganic nutrients to survive and grow. These requirements are metabolized through the roots and foliage. Any interruption in the availability of these materials, or in the pathways of uptake, will disrupt the normal physiological and metabolical processes of the tree.[65]

Relationships between various causal agents and maple decline, or forest decline in general, have been popularly conceptualized in forest pathology as *inciting, predisposing,* or *contributing* factors.[68]

Inciting factors are intense stresses, usually of short duration, which can cause severe injury. Examples of *inciting* factors include defoliating insects, such as spruce spanworm or forest tent caterpillar, severe drought, flooding, frost, weather extremes, and acute fumigations of phytotoxic air pollutants. *Inciting* factors may kill trees outright.

Predisposing factors tend to be long-term or endemic. Examples include subtle climate stress, impoverished soil or poor site, tree genetics, advanced tree age, and chronic pollution levels. These factors impose a permanent stress on the forest ecosystem, resulting in reduced tree vigour that in turn renders the tree more susceptible to damage from other agents. *Predisposing* factors rarely directly result in tree mortality but are significant links in the decline cycle.

Contributing factors can also be long-term in nature or endemic to the forest ecosystem. These include bark beetles, canker fungi, root and wood rot fungi and viruses. *Contributing* factors find it easier to infect, and may even act more aggressively in trees that have been weakened by *predisposing* or *inciting* factors. The *contributing* agents may eventually kill trees that are in a weakened condition. Usually, healthy trees that have not been adversely stressed by the various *predisposing* and *inciting* factors are capable of resisting infection or even recovering from *contributing* stresses. Atmospheric pollutants, such as acidic precipitation and ozone, are hypothesized to act as either *predisposing* or *contributing* factors leading to tree decline.

Table 1 summarizes the various causal agents reported to be associated with maple decline in 189 published documents.[71] These data illustrate that insects and disease were each cited as inciting causal agents in just less than 20% of the maple decline reports. *Armillaria* root rot, commonly called honey fungus or shoe string root rot, was the most frequently cited fungal pathogen (5.8% of the reports). Forest tent caterpillar was the insect that was most often concluded as inciting maple decline (7.4% of reports). Slightly more than 17% of the reports implicate adverse climate and about 12% identify pollution as contributing to the decline episode. Causal agents could not be identified in more than 15% of the cases. Clearly, maple decline is a complex phenomenon frequently involving many potential causes.

Table 1
Summary of Causal Agents Associated with Sugar Maple Decline.

Causal Agent	% of Reports
Armillaria root rot	5.8
other diseases	13.8
forest tent caterpillar	7.4
nematodes	2.6
other insects	9.6
temperature extremes	10.6
drought	6.9
salt	5.3
herbicide	2.6
air pollution	2.2
acid rain	2.1
cultural practices	3.2
mechanical injury	2.6
nutrient deficiency	2.2
miscellaneous	15.3
unknown causes	7.9

Data based on 189 published reports of maple decline, adapted from McIlveen et al, 1986.[71]

7.1.3 Historical Perspective

Maple decline is not a recent phenomenon, nor is it restricted geographically. It was first reported in 1913 in Pennsylvania and New Jersey.[49] In the 1920s and 1930s, maple decline occurred in several states in the northeast U.S. The first reported Canadian incidence of maple decline was in 1931-32 (and again in 1962) in the Beauce County area south of Quebec City.[28] The first reported incidence of maple decline in Ontario appeared in 1947-48.[82] Many references originated from the Lake States and Ontario throughout the 1950s and 1960s.[27, 28, 44, 52, 98] The MOE first investigated maple decline that occurred over 8100 ha in the Parry Sound area in 1978. As recently as 1980, the Forest Insect and Disease Survey (FIDS) of Forestry Canada monitored maple decline on 25,000 ha in Algonquin Park, 8,000 ha in Parry Sound, and 500 ha in Owen Sound. Tree mortality exceeded 25% in these areas.[37]

The number of sugar maple decline episodes appears to be increasing dramatically. For example, of 102 published reports in Ontario, 65 were recorded after 1975. However, it is not certain whether this actually represents an increase in the extent of the problem or simply an increase in the frequency of reporting. Currently, maple decline is a problem in some parts of Ontario, in scattered locations across the northeast U.S., and perhaps in New Brunswick.[72] Unquestionably the most severe and extensive decline episode in recent history is occurring in Quebec in a large area mostly south of Quebec City.[42]

7.2 Effects of Long-Range Atmospheric Pollutants

7.2.1 Relative Economic Impact

To date, there is no conclusive evidence to link forest decline in eastern North America directly to long-range atmospheric pollutants, such as acidic deposition and ozone. The methods of determining direct cause and effect dictate that a causal relationship can be inferred only when there is a strong consistent pattern of response and a proven biological mechanism with the suspected causal factors. The pollution/forest decline connection is very difficult to prove because the forest is a complex, elastic and dynamic ecosystem that is constantly reacting to many interrelated natural and anthropogenic stresses.

A comprehensive economic impact evaluation has not been conducted on the effect of atmospheric pollution on Canadian forests. The relative value of the eastern Canadian timber harvest in 1981 was approximately $3.93 billion. It has been hypothetically speculated that if the effect of atmospheric pollution is to reduce forest productivity by 5% annually, then the estimated loss to the timber industry in 1981 would have been about $197 million.[14] However, this is a misleading conclusion because the (5%) rationale is unsubstantiated and it does not take into account the cumulative nature of a reduction in forest productivity. A loss of productivity could both reduce the allowable annual harvest and lengthen the harvest rotation period. In addition, any value associated with a reduction in annual productivity could potentially increase dramatically with time as the volume of the current annual increment declines. Most of the value of the timber harvest is associated with the northern boreal forest. But the pollution gradient in Ontario is distinctly north-south, so that the boreal forest would be less affected and the hardwood forest in the south would be more affected. Therefore, productivity loss in the hardwood forest may be proportionately larger. And since both the market value and the potential value added with furniture or veneer quality hardwoods are higher than northern softwood, the economic impact of the effects of air pollution may be substantially greater in Ontario's hardwood forests. The estimated economic loss due to air pollution would be increased substantially if values for the destruction of fish and wildlife habitat,

the disruption of recreation, and the associated loss in tourism were considered. These non-timber losses for eastern Canada have been estimated, again speculatively, at $1.29 billion (1981 $CDN).[14] Timber and non-timber losses are not entirely additive because economic gain obtained through timber harvest may be partially forfeited if the trees are left standing to provide tourism or recreational opportunities.

These figures give an idea of the magnitude of a potential economic impact on the forest resource. However, it is a superficial and incomplete evaluation. Opportunity costs, multiplier effects, and other economic considerations are not addressed. What is clear at this time, even though a detailed assessment has not been conducted, is that the potential economic impact of a loss of forest productivity is enormous.

7.2.2 Injury Pathways

Atmospheric pollutants can cause injury to the forest ecosystem either directly or indirectly. Pollutants can react directly with the tree crown. Because leaves and flowers are relatively short-lived, these effects are usually felt in the current growing season. For some tree species the effects may be lagged into the subsequent season. Pollutants deposited onto the soil react indirectly on the forest ecosystem. Subtle chemical reactions with the soil can affect nutrient availability, adversely affect soil insect populations, and inhibit tree root growth. Indirect effects through the soil may take years, decades, or longer, depending on the soil characteristics and the pollution deposition rate.

7.2.2.1 Direct Effects

Foliar effects of acidic deposition have been extensively studied. It has generally been concluded that visible foliar injury does not occur unless the leaves are continuously exposed to rainfall with a pH of 3.0 or lower. On average, the acidity of rain in Ontario in the area of highest deposition seldom falls below pH 4.1. Rainfall pH averages about 4.2 in the hardwood forests of southcentral Ontario.[105] However, foliar metabolic processes can be disrupted without producing visible symptoms. Some of theses subtle non-visible effects have been produced in some tree species in laboratory experiments using artificial acidic precipitation at ambient pH levels.

The integrity of tree leaves is protected by an epidermal layer of outermost cells and a waxy cuticle. They prevent the loss of moisture and other cellular constituents and inhibit the invasion of micro-organisms. It is thought that wet acidic deposition may accelerate the erosion of the leaf cuticle and damage the epidermis, increasing the rate of loss of internal cellular nutrients, thereby hastening leaf senescence. Also, acidic deposition interferes with the function of leaf guard cells resulting in a loss of stomatal control, thereby altering the leaf's rate of transpiration and gas exchange.[104] Leaves injured in this fashion may be more susceptible to foliar pathogens and more vulnerable to other environmental stresses. This could lead to a reduction in net photosynthesis, that in turn would result in reduced tree vigour and possibly less incremental growth.

Acidic deposition has been shown to interfere with spermatatoid activity and pollen tube elongation. Therefore, particularly acidic events during the period of flower development could affect the resultant seed production.

Ozone may be acting synergistically with acidic precipitation to increase the potential for foliar effects at the current ambient levels. Ozone concentrations in southwestern Ontario in the summer are regularly high enough to cause visible injury to sensitive tree species, such as green ash, basswood and Manitoba maple. Even at sub-acute levels, ozone can damage cell membranes, thereby increasing permeability, which in turn, makes the leaf more susceptible to nutrient leaching by acidic deposition.[20]

7.2.2.2 Indirect Effects

Indirect effects are the result of the reactions between the soil and chronic atmospheric deposition. The acidic components in rainfall and snow can react chemically with sensitive soil types to lower soil pH and increase nutrient leaching and metal mobilization. Tree nutrient deficiencies can develop if the rate of nutrient leaching from the soil exceeds the rate of nutrient input through weathering of parent material and decomposition of organic matter.

As soil pH decreases, both the variety and number of soil micro-organisms also could decrease. Soil micro-organisms are responsible for recycling nutrients through decomposition of organic matter. Soil affected by acidic deposition may therefore have significantly slower nutrient turnover, which exacerbates the problem of nutrient deficiency induced by accelerated soil leaching.

Changes in soil chemistry may interfere with the tree root mycorrhizal relationship. Mycorrhizae are fungi that grow on (and into) the fine feeder roots of trees. These fungi are essential to tree health because they assist the roots in extracting water and other elements from the soil.

In addition to nutrients, soil contains many other inorganic elements, some of which can be phytotoxic. The total concentration of these elements in the soil may be quite high, but they are generally not plant-available because they are immobilized at higher soil pH levels. As the soil pH is reduced, these elements become more mobile (plant-available concentration increases) and may reach potentially phytotoxic concentrations. Aluminum (Al) is the element of greatest concern because it is known to be toxic to tree roots. Plant-available Al soil concentrations increase very rapidly with relatively small decreases in soil pH.

Soils vary substantially in their sensitivity to acidification by acidic deposition. Generally, soil sensitivity increases with decreasing organic matter content, cation exchange capacity, pH, base saturation, exchangeable bases, $CaCO_3$ concentration, and increasing sand component. Therefore, the shallow, coarse-textured, poorly-buffered and nutrient poor soils characteristic of large areas of the Precambrian Shield in northern and central Ontario are more sensitive to accelerated acidification than are soils in the southern portion of Ontario that are derived from calcareous parent material and tend to be deeper, finer textured and generally well buffered.

7.3 Major Hypotheses of Forest Decline

At last count, there were more than 186 theories on the relationship between atmospheric pollutants and forest decline. However, most are variations or regional examples of one of six major hypotheses.[51] These hypotheses are: 1) general stress, 2) soil acidification and root toxicity, 3) ozone injury, 4) excessive/accelerated nutrient leaching, 5) excessive fertilization, and 6) growth-altering organic compounds.

The general stress hypothesis suggests that forests have been exposed to several decades of sub-acute air pollution mixtures. This decreases the photosynthetic efficiency of trees, reduces vigour and disturbs the energy budget. The normal production within the tree of natural protective chemicals, such as phenols and terpenes, is reduced, therefore increasing susceptibility to insects, disease and other stress factors. The trees subsequently die of natural causes, thereby obscuring the anthropogenic connection.[51]

The soil acidification and root toxicity hypothesis suggests that natural acidification of forest soils is accelerated by acidic deposition.[69] Nutrients essential for tree growth are leached from the soil at a rate exceeding replacement, thereby inducing nutrient deficiencies. At the same time, potentially toxic elements, like Al, increase in availability as soil pH decreases, resulting in root mortality. Reductions in fine root biomass inhibit the trees' ability to supply moisture and nutrients, resulting in crown dieback, which mimics moisture and/or nutrient stress.

The ozone hypothesis suggests that photo-chemical oxidant pollutants directly incite tree decline by injuring the foliage through chronic exposure.[127] A reduction in photosynthetic capacity leads to reduced carbon assimilation and eventually less biomass production. Ozone injury causes the leaf cells to be more permeable and therefore more accessible to the tissue leaching potential of wet acidic deposition. It also weakens the leaf's cuticle, which is a natural barrier to secondary pathogens.

The accelerated foliar leaching hypothesis suggests that important plant nutrients, such as Mg, K, Zn, Ca, and Mn, are leached from foliage through chronic exposure to acidic deposition.[127] The trees may develop Ca and Mg deficiency symptoms in the crown where these elements are in marginal supply in the soil. Some trials in Europe and Quebec have been successful in reviving symptomatic trees by soil fertilization with the deficient element, as diagnosed by foliar analysis.

Acidic deposition contains nitrogen as well as sulphur. The excessive fertilization hypothesis suggests that the forest may be over-fertilized with nitrogen. Trees may absorb nitrogen from deposition directly through the foliage.[112] Over-fertilization with nitrogen encourages rapid growth, creating a demand for additional nutrients that may not be available in the required amount from the soil. Nitrogen over-fertilization also results in late season growth and inhibits the development of cold hardiness, therefore making the tree more susceptible to frost damage or winter injury.

The growth-altering organic compounds hypothesis is somewhat speculative. This theory recognizes that in addition to the "normal" air pollutants, there are numerous organic compounds in the atmosphere. Some of these compounds are, or may mimic, natural plant hormones, thereby possibly adversely altering tree growth.[127]

7.4 Regional Atmospheric Pollution Gradients in Ontario

Air pollution levels, including acidic deposition, vary widely across the province. There are distinct regional trends towards higher levels in the southwest and lower levels in the northwest. This pattern reflects the concentration of industrial activity in southwest Ontario and the proximity to large U.S. centres in the lower Great Lakes Basin and farther south.

Figure 1 illustrates mean precipitation pH contours in Ontario for the period 1981 to 1984. Precipitation pH ranges from less than 4.2 in areas around Lakes Ontario and Erie and a section between Georgian Bay and Lake Nipissing, to greater than 5 in the extreme northwest boreal forest and the James Bay/Hudson Bay lowlands. Precipitation in the hardwood forest region in Ontario has averaged pH 4.2 to 4.3 for at least the last 15 years.[105]

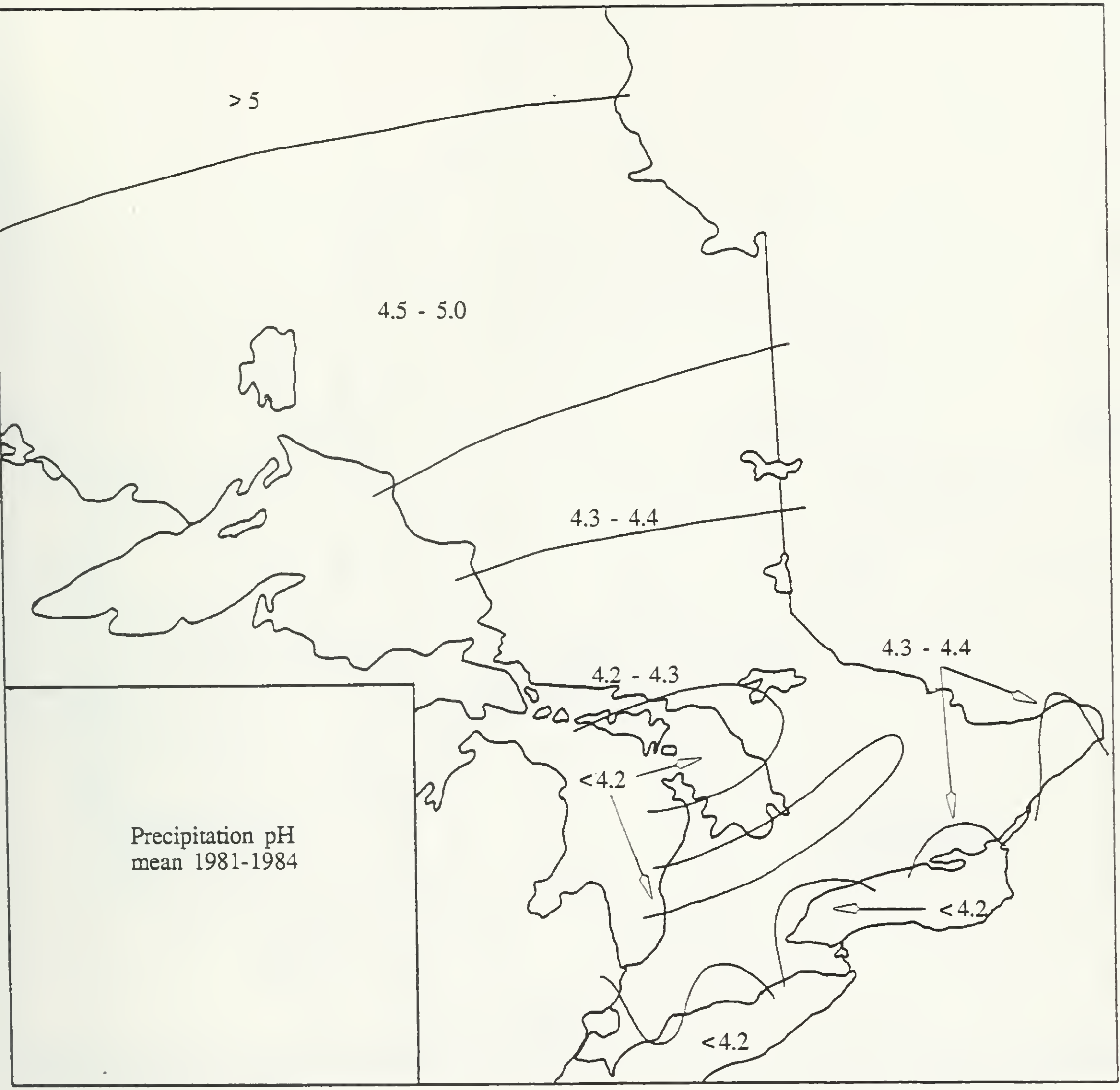
Figures 2 and 3 illustrate the four year (1981-1984) mean wet and dry sulphate deposition respectively. Deposition in the hardwood forest region has averaged between 20 and 35 kg/ha/yr wet sulphate and between 4 and 24 kg/ha/yr dry sulphate. In southern Ontario, the wet deposition of sulphur averaged about two times the dry deposition levels, whereas in central and northern Ontario the wet:dry sulphate deposition ratio is nearer 4:1.[105]

Wet and dry nitrate deposition over this same period are illustrated in Figures 4 and 5 respectively. The hardwood forest region of Ontario receives between 3 and 5 kg/ha/yr wet nitrate and between 2 and 4 kg/ha/yr dry nitrate deposition.[105] The wet and dry nitrate deposition ratios are similar across the province.

An annual wet sulphate deposition rate of about 20 kg/ha/yr is generally considered as the damage threshold for sensitive aquatic ecosystems. A threshold for damage to terrestrial ecosystems has not been established.

Air parcel trajectory analysis has shown that approximately 80% of the sulphate and nitrate deposition in southwest Ontario and approximately 60% in the southeast of the province originates from sources in the U.S.[105]

Sulphate deposition in Ontario is highest in the summer and lowest in the winter. Nitrate deposition is marginally higher in the winter. Acidity deposited in the winter accumulates in the snow. It is released during the spring, creating a shock of acidity that pulses through the ecosystem with the melt water. This "acid shock" effect can have serious environmental implications, in that this short period of low acidity may be more damaging than the less acidic conditions that occur for the rest of the year.



adapted from Tang et al (1986)

Figure 1
Mean Precipitation pH in Ontario (1981-1984).

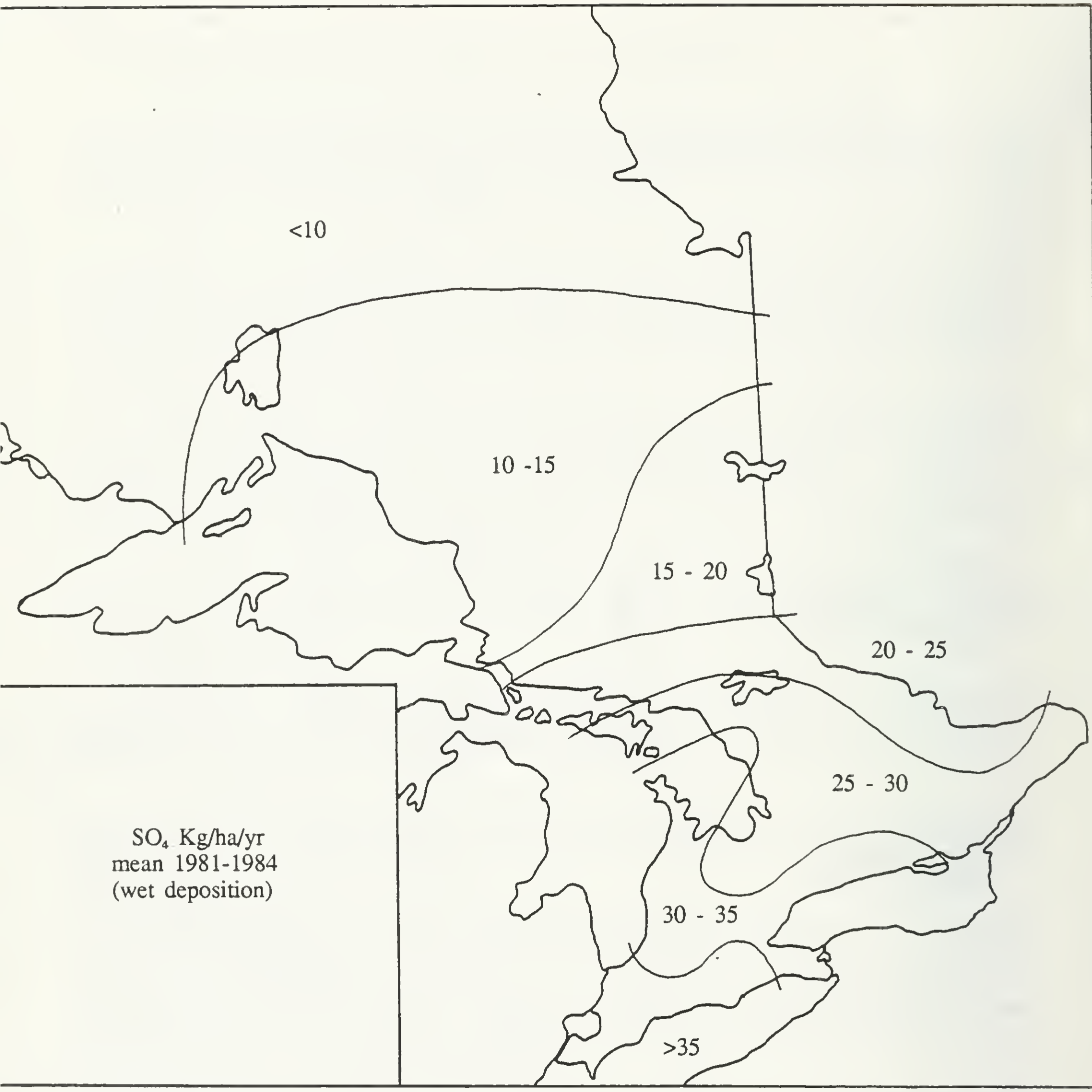


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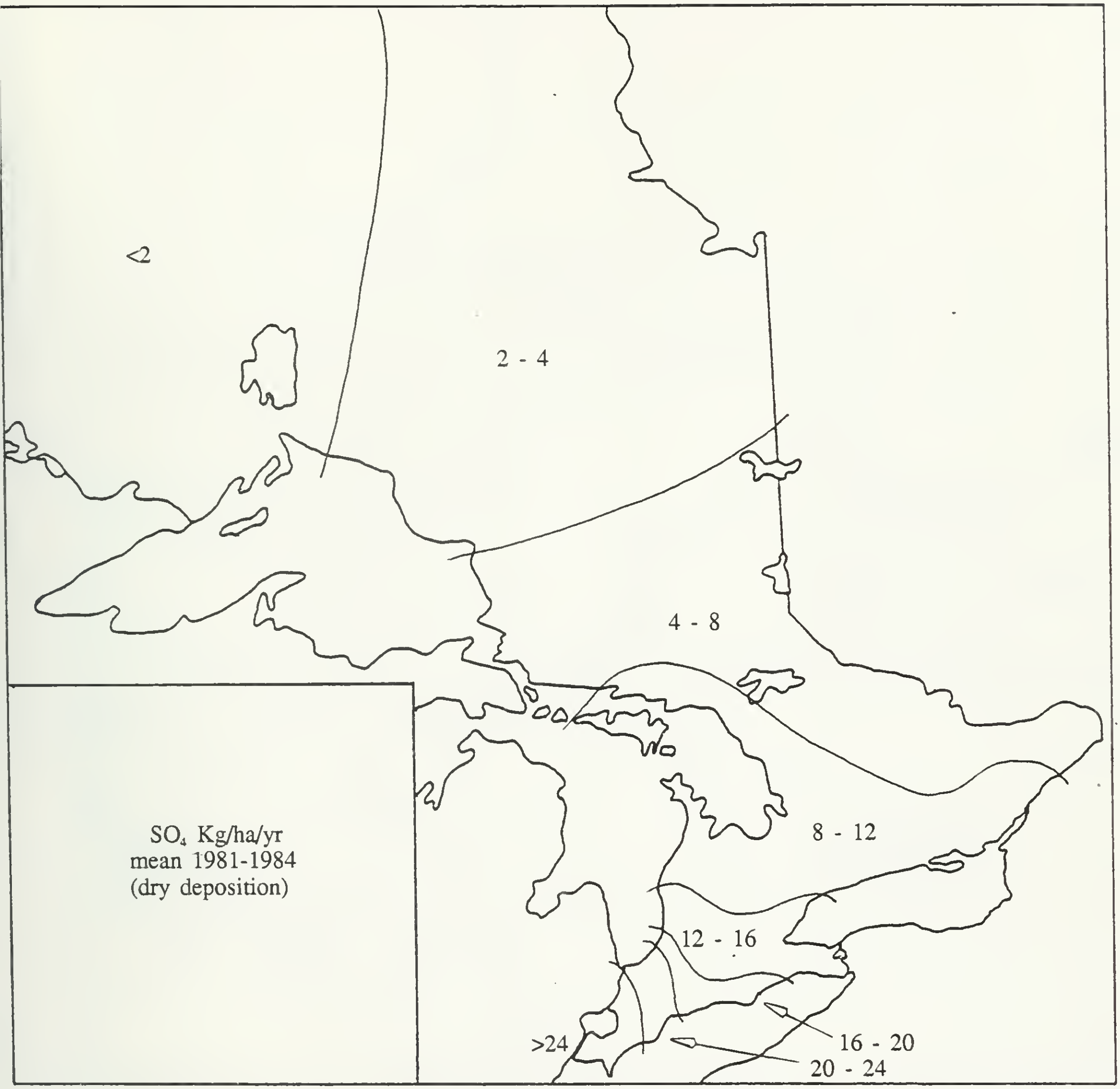
Figure 2
Mean Wet Sulphate Deposition in Ontario (1981-1984).



adapted from Tang et al (1986)

Figure 3
Mean Dry Sulphate Deposition in Ontario (1981-1984).

Figure 4
Mean Wet Nitrate Deposition in Ontario (1981-1984).

adapted from Tang et al (1986)

Figure 5
Mean Dry Nitrate Deposition in Ontario (1981-1984).

Figure 6 illustrates the mean growing season daylight ozone concentration in Ontario for the period 1974 to 1981. Unlike sulphate and nitrate, ozone is non-accumulative and is phytotoxic only at elevated ambient concentrations and only when the plants are photosynthetically active. Ozone concentrations are highest in the southwest and along the north shore of Lake Ontario, adjacent to the large industrial and urban centres.[64]

The seven hour growing season (June to August) mean ozone concentration in Ontario rarely exceeds 50 parts per billion (ppb), even in the southwest, although considerable variation occurs. Short term hourly ozone peaks greater than 100 ppb occur most summers. Generally, 80 ppb is the level at which many sensitive plant species can develop visible foliar injury. Phytotoxicology surveys have documented ozone injury on susceptible agricultural and ornamental plants across the southwest, central and southeast regions of the province. Foliar injury characteristic of ozone also has been observed in the Sudbury area. This suggests that Figure 6 may understate the ozone concentration in northcentral Ontario (there are far fewer monitoring stations in the north).

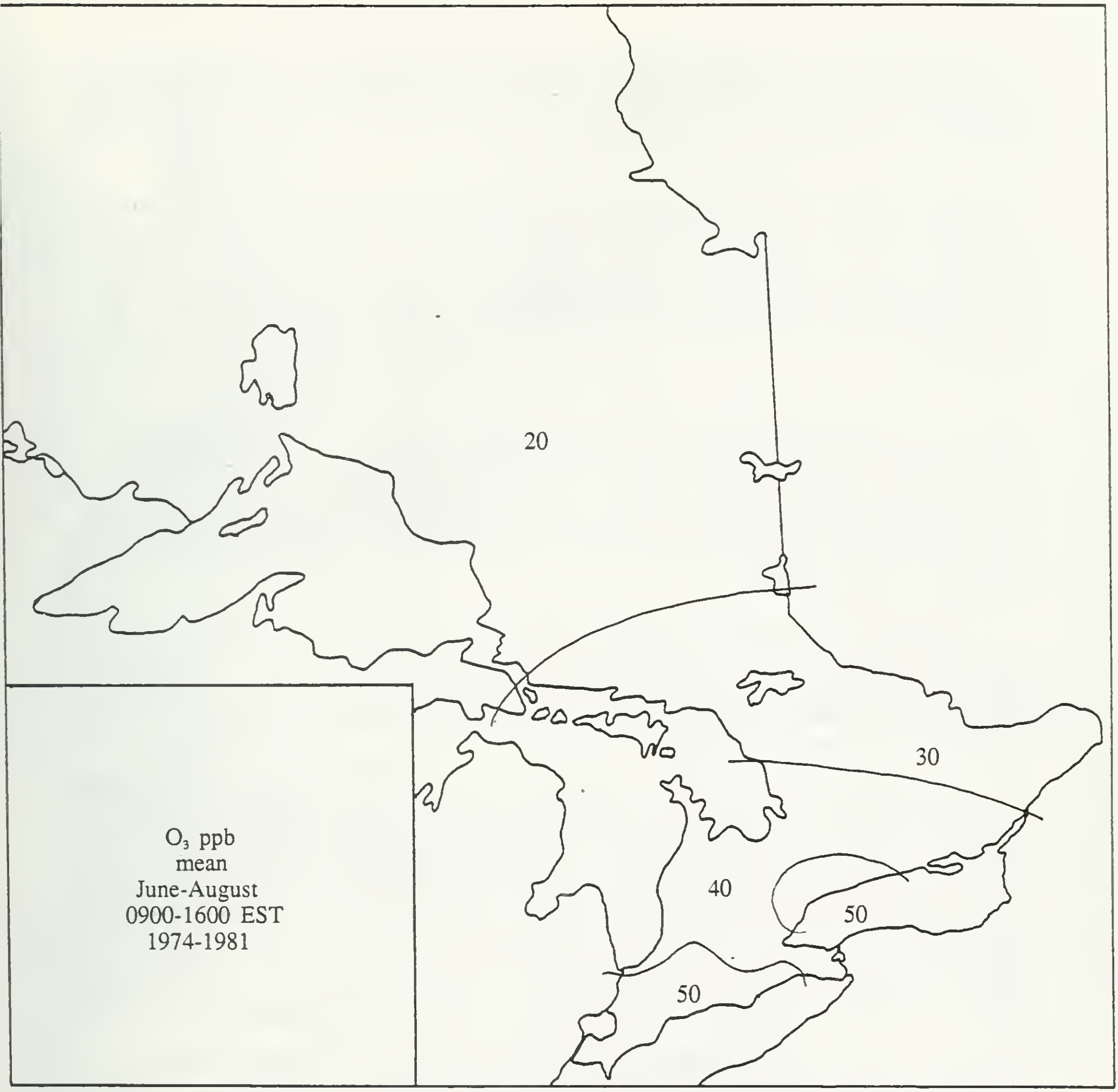
Trees vary considerably in their foliar sensitivity to ozone. Green ash, Manitoba maple and basswood are among the most sensitive. Ozone-like foliar injury on these species is observed most summers in southern Ontario. By comparison, sugar maple is considered to be moderately tolerant to ozone, based on foliar injury.[73] Foliar injury characteristic of ozone has not been observed on sugar maple in Ontario.

Ozone may disrupt foliar metabolic processes at ambient concentrations below those necessary to cause visible foliar injury. Ozone also may interact synergistically with acidic deposition to impose a greater stress on the forest than either of the two air pollutants separately.

8.0 Maple Decline in Ontario: Current Status

The current status of sugar maple decline in Ontario was assessed in three ways. First, a letter was sent in September 1984 from the MOE's APIOS office to all MNR district offices requesting information on the extent and severity of maple decline in their jurisdiction. Second, in the fall of 1985 a survey was prepared co-operatively by the MOE and OMAF and distributed to all members of the Ontario Maple Syrup Producers Association (OMSPA). Third, in response to information received from the MNR and concerns expressed by the OMSPA, in 1986 the MOE initiated an extensive province-wide Hardwood Forest Health Survey.

All MNR offices responded to the MOE letter. MNR offices reporting maple decline in 1984 included Algonquin Park, Minden, Parry Sound, Huronia, Lindsay, and several others in the southwest region of the province. Offices in the central and southeast regions of Ontario reported that maple decline was not considered a problem.



adapted from Linzon et al (1984)

Figure 6
Mean Growing Season Daylight Ozone Concentration in Ontario (1974-1981).

Those offices reporting maple decline stated that the current episode started in the late 1970s and appeared to occur in isolated pockets. Decline was most frequent in areas of recent insect defoliation and in woodlots with poor management regimes, however, this was not consistent and many cases of "unknown causes" were reported.

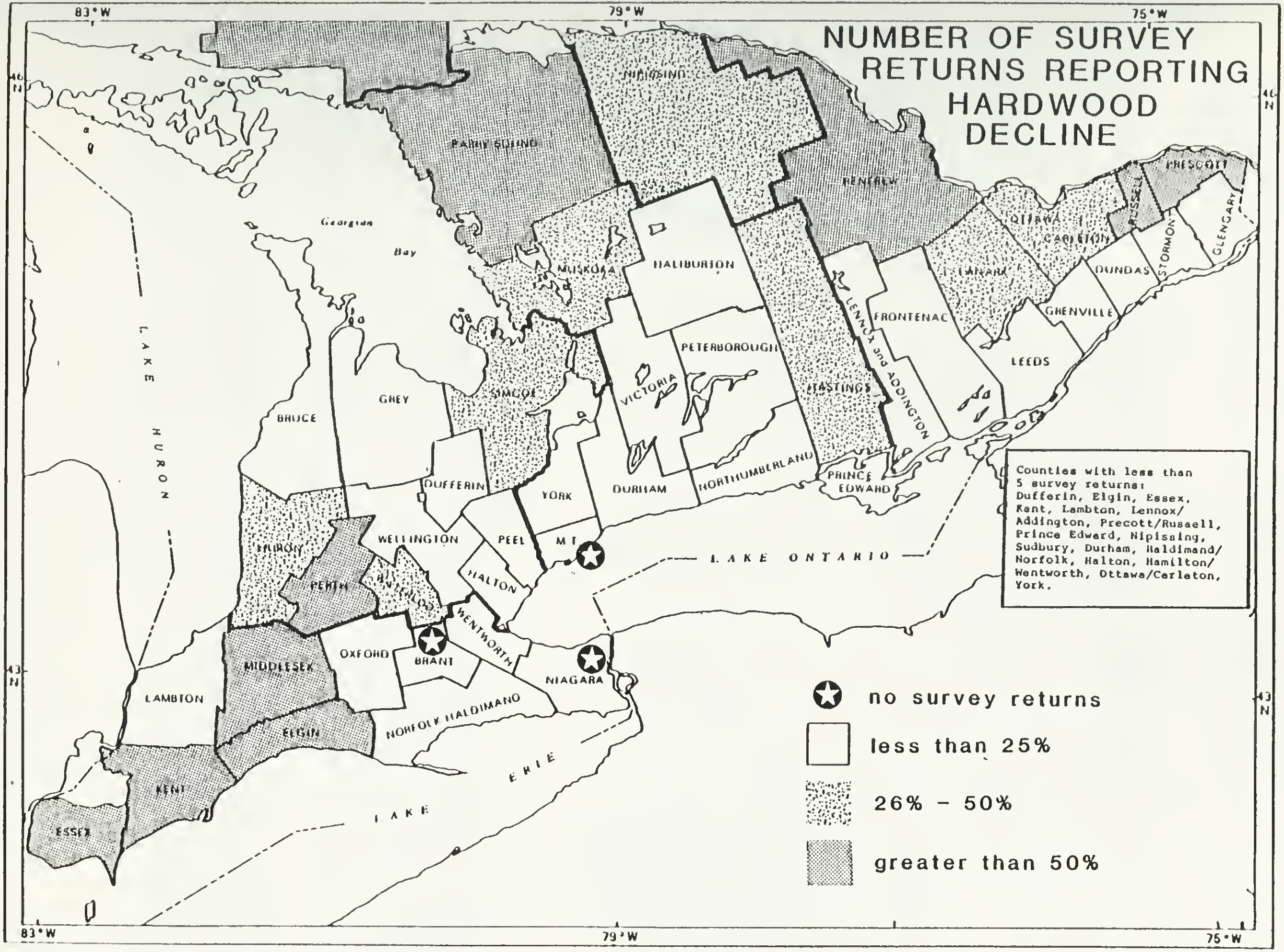
Just over half of the 610 surveys sent to the OMSPA members were returned, representing all geographic regions of the hardwood forest. The survey data have been summarized and released as an MOE report.[75] One third of the respondents claimed that, in their opinion, hardwood tree decline was currently (1985) a problem in their woodlot. Of the 33% reporting decline, 72% said it was getting worse, and 89% said they had not experienced a similar decline in their woodlot. The most frequently cited year in which symptoms first became apparent was 1982 (20%), followed by 1980 (17%).

Figure 7 illustrates the distribution of maple decline in Ontario, by county, as reported by the OMSPA survey. These data indicate that maple decline in woodlots used to produce maple syrup products was most frequent in areas adjacent to Georgian Bay, Algonquin Park, the Ottawa valley, and in counties in southwest Ontario. Decline was infrequently reported in the Bruce Peninsula, the eastern end of Lake Erie, around Lake Ontario, the south central part of the province, and along the north shore of the St. Lawrence River. These data are in general agreement with information obtained from the MNR offices.

The province-wide Hardwood Forest Health Survey was initiated by the MOE in 1985, completed in 1986, repeated in 1987, and again in 1989, 1990, and 1991. In total, 110 permanent forest observation plots were established, each containing 100 trees greater than 10 cm in diameter. Rigorous selection criteria ensured plot uniformity and representative geographical distribution of the 11,000 trees in the survey.

Decline status of the trees was determined with a crown condition assessment developed specifically for the survey by MOE scientists and modified by the consulting company that undertook the program. The crown condition assessment procedure will be described in detail in Section 9.4. Briefly, the assessment procedure combines field observations of branch dieback and foliar colour and size into a numeric value called a Decline Index (DI).[76] The DI ranges from 0, a healthy tree with no symptoms, to 100, which represents a dead tree. On a relative scale, trees with a DI of 12 and lower would be considered healthy. A DI of between 13 and 20 identifies a tree in a light decline class. A DI of between 21 and 30 represents a tree in a moderate decline class. Trees with a DI between 31 and 50 are in a high decline class, and over 50 is severely declining.

Mean DI values were calculated for various data stratifications, including species and regional distribution. The results of the first few years of the survey are summarized in detail in a separate MOE report.[72] Sugar maple was the target species, comprising 75% of all trees tallied. Tree condition data were also collected for 21 other species, although only nine species each comprised more than 1% of the survey sample population. Table 2 summarizes the mean DI in 1986 for the nine tree species for which reliable data were collected. Sugar maple had a mean DI of 12, the lowest of the group, i.e., is in the "best" condition. However, the survey was highly biased towards sugar maple.



adapted from McLaughlin and Butler (1987)

Figure 7
Distribution of Maple Decline in Ontario in 1986, by County, as Reported by Members of the Ontario Maple Syrup Producers Association.

Table 2
Relative Condition of Nine Hardwood Tree Species in Ontario (1986).

Tree Species	% of Survey Total	Mean Decline Index
Sugar Maple	74.8	12
American Beech	3.0	13
White Ash	3.7	17
Basswood	3.0	18
Yellow Birch	1.7	20
Red Oak	1.5	20
Red Maple	3.1	22
White Birch	1.0	24
Black Cherry	1.6	28

-based on a survey of 11,000 trees surveyed in 1986, adapted from McIlveen et al (1989).[72]

These data suggest that hardwood tree species in addition to sugar maple are experiencing decline, and relatively speaking, sugar maple may be in better condition than many other hardwood trees in Ontario.

There are two recognized hardwood forest regions in Ontario, the Deciduous and the Great Lakes St. Lawrence (Forest Regions). These are further divided into nine Forest Sections, based largely on species composition, which are in turn related to gross soil and macroclimate regimes. Figure 8 illustrates the mean DI in 1986 for each Forest Section. Regional differences are apparent. The mean DI is highest in the area between Georgian Bay and Algonquin Park, and across the northern edge of the hardwood forest range. The southwest is also an area of (relatively) high decline. In contrast, decline indices are lowest across south central and southeast Ontario.

Fisher's Least Significant Difference test was used to determine if the differences between decline indices for the various Forest Sections were statistically significant. At $p<0.01$ (less than 1% chance that the results are *not* different) the mean DI must be more than 4.7, and at $p<0.05$ (less than 5% chance), the DI difference must be at least 3.0 to be statistically significant.

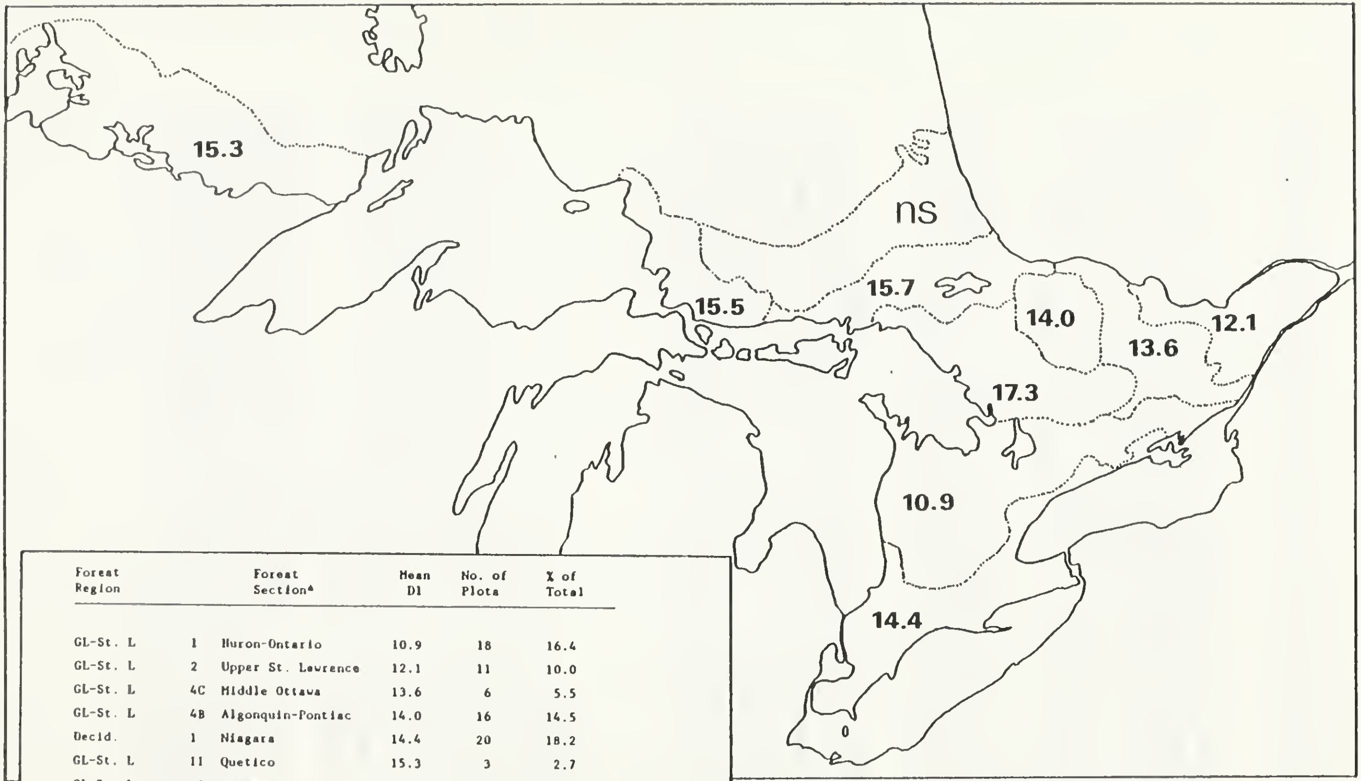
The survey data confirmed observations by the MNR and the OMSPA that, in the mid-1980s, maple decline was a scattered, isolated phenomenon in Ontario, although regional patterns were apparent. The geographic distribution of maple decline in Ontario correlates only superficially with atmospheric pollution. Decline is prevalent in the southwest where pollution levels, particularly ozone, are highest. Higher rates of decline occur in the central and northern regions where pollution levels are lower. However, these areas are also much more sensitive to potential indirect pollution effects because of the shallow, poorly-buffered soils of the Precambrian Shield. Forests on the shield may be predisposed to decline as a result of their inherent sensitivity to environmental stress.

9.0 Results of Etiology Study

9.1 Study Sites: Location and Study Design

The study of the etiology of sugar maple decline was conducted at 11 woodlots. Eight of the study sites were in the Muskoka area, two were east of Peterborough, and one was northwest of Thunder Bay (see Figure 9). The sites were chosen in consultation with the OMSPA, OMAF, and the MNR. They were selected because they represented a gradient of decline severity, from quite healthy to significant decline, although declining trees were evident at all sites. The study sites were also selected to represent a gradient of management regimes.

The sites also were selected across a pollution gradient. The two sites near Peterborough receive an average of 30 to 35 kg/ha/yr wet sulphate deposition and about 50 ppb ozone as a seven hour (daylight) growing season mean. The Muskoka area sites receive between 30 and 40 ppb ozone and between 25 and 30 kg/ha/yr wet sulphate deposition. By comparison, the Thunder Bay site, which was selected as an air pollution control, receives less than 15 kg/ha/yr wet sulphate deposition and about 20 ppb ozone during the growing season.



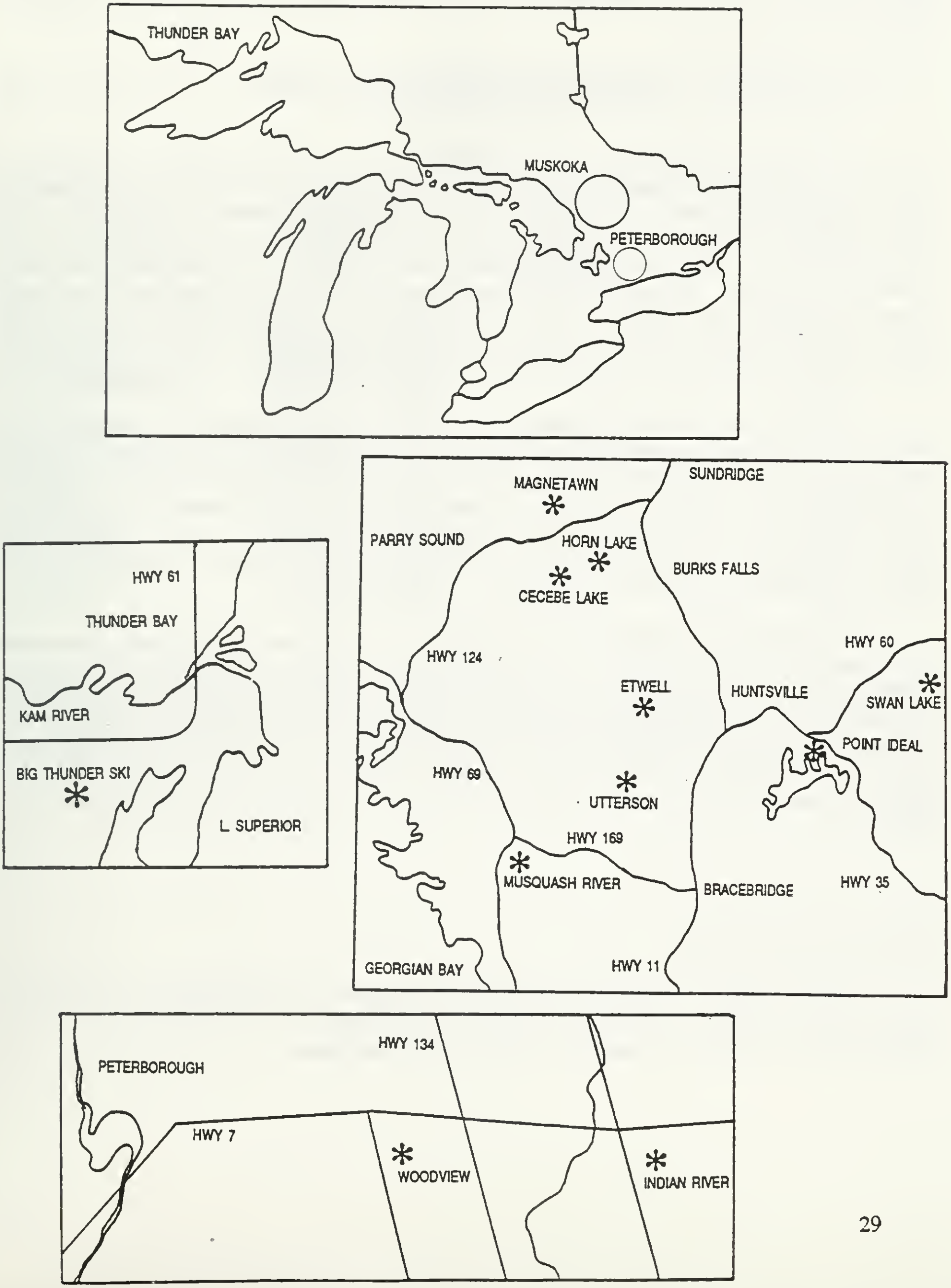
Forest Region		Forest Section*	Mean DI	No. of Plots	% of Total
GL-St. L	1	Huron-Ontario	10.9	18	16.4
GL-St. L	2	Upper St. Lawrence	12.1	11	10.0
GL-St. L	4C	Middle Ottawa	13.6	6	5.5
GL-St. L	4B	Algonquin-Pontiac	14.0	16	14.5
Decid.	1	Niagara	14.4	20	18.2
GL-St. L	11	Quetico	15.3	3	2.7
GL-St. L	10	Algoma	15.5	11	10.0
GL-St. L	4E	Sudbury-North Bay	15.7	13	11.8
GL-St. L	4D	Georgian Bay	17.3	12	10.9
Least Significant Difference (at <0.01)			4.7		

forest classification after Rowe (1972)
ns - region not surveyed

adapted from McIlveen et al (1989)

Figure 8
Mean Decline Index of Nine Forest Sections in Ontario, Based on the 1986 Survey of 11,000 Trees.

Figure 9
Location of the 11 Intensively Studied Woodlots Utilized for the Sugar Maple Decline Etiology Study.



Ten of the 11 study sites were located in privately owned woodlots. These sites are identified in the report either by the nearest community or a nearby lake, rather than by the name of the woodlot owner. One site was established in the MNR Swan Lake Silvicultural Research Station in Algonquin Provincial Park.

The Thunder Bay and Muskoka-area sites were established in 1984. The Swan Lake and the two Peterborough-area sites were established in 1985.

A permanent observation plot with a minimum dimension of 20 m by 20 m was established at each site, and all trees greater than 10 cm diameter at breast height (dbh) were identified with sequentially numbered plastic tags. Individual tree co-ordinates were recorded at each site and maps were prepared to aid in tree location on return visits. All tagged trees were assessed for decline symptoms with the Decline Index assessment methodology used in the province-wide Hardwood Forest Health Survey. Complete site and management histories were obtained from the woodlot owners. Entomology and pathology surveys were conducted at each site. Weather records from the nearest weather stations were examined. Stand mensurational characteristics were determined. A soil pit was dug to classify the soil at each site and determine it's sensitivity to acidic deposition.

At each site six additional co-dominant trees were selected for destructive sampling. These trees were adjacent to the permanent observation plots. The sampled trees were rated for decline symptoms to ensure they represented an adequate decline gradient (3 trees healthy and 3 trees at least in moderate decline). Foliar, root, and soil samples were collected and analyzed for 21 elements (detailed in Section 9.5). Wood plugs were collected from the root collar for starch analysis. Tree growth patterns were examined with increment cores obtained from all six trees at each site and with detailed stem analysis of at least two trees from each of 10 sites.

Ground and aerial observations of the study sites, and the study area in general, confirmed that maple decline was present in various degrees of severity. Severe decline occurred in scattered, isolated pockets and more frequently on higher and more exposed sites. However, this pattern was not consistent. Occasionally, a few severely affected trees were observed distributed among healthy trees in an otherwise unaffected woodlot. In some areas, most of the mature sugar maple over several ha exhibited thin crowns with slightly chlorotic foliage. There were also expansive areas within the general study area where no decline symptoms were evident and the forest looked very healthy.

9.2 Site Characteristics

Table 3 identifies the study sites and briefly summarizes the management status and the relative pollution loading. Six of the 11 sites have been tapped for maple syrup production on a commercial basis, and one was tapped for personal syrup production.

Table 3
Study Site Management Status and Relative Pollution Loading.

Study Site	Management Status[1]	Sulphate Deposition[2] kg/ha/yr	Ozone[3] ppb
Magnetawan	commercially tapped	30	30
Horn Lake	recreationally tapped	30	30
Cecebe Lake	historically logged	30	30
Etwell	commercially tapped	30	40
Point Ideal	commercially tapped	30	40
Musquash River	historically logged	35	40
Utterson	commercially tapped	30	40
Swan Lake	silvicultural research	30	40
Woodview	commercially tapped	35	50
Indian River	commercially tapped	35	50
Thunder Bay	historically logged	10	20

1 - trees have been tapped to produce maple syrup.
2 - wet sulphate deposition, mean 1981-1984, from Tang et al (1986).[105]
3 - ozone concentration is growing season daylight mean 1971-1981, from Linzon et al (1984).[64]

These sites are also thinned regularly, partly to provide fuel wood for evaporation and partly as management practice to promote crop trees. Cecebe Lake and Thunder Bay have not been tapped nor have they been recently logged. The Musquash River site has not been recently logged but historical logging has been quite heavy. The Swan Lake site is the least disturbed. It has never been tapped for syrup production and the last logging was a selective cut in the 1920s, in which mature yellow birch and some sugar maple were removed.

Tables 4 and 5 summarize the basic stand mensurational characteristics. Mean basal area ranged from a low of 14 m^2/ha (Utterson) to a maximum of 41 m^2/ha (Musquash River). All three MNR site classes for tolerant hardwoods were represented. Stand age, estimated from the increment cores collected at dbh for the six sampled trees at each site, ranged from 65 years at Horn Lake to 120 years at Swan Lake. This under estimates age, of course, because the time required to reach dbh (about 1.3 m) is unknown. One of the six sampled trees at Swan Lake was considerably older than the other five co-dominants (in excess of 270 years). Therefore this one tree was not included in the mean stand age listed in Table 4. Also, this implies that the estimate of stand age at this site is conservative.

The proportion of the sugar maple component varied considerably between the study sites, ranging from about 29% at Musquash River to almost 97% at Indian River. At Musquash River, soft maple (mostly red and some silver) comprised 47% of the stand; therefore the total maple component at this study site was 77%. Associated tree species at the study sites included black, red, and silver maple, American beech, white and yellow birch, basswood, black cherry, trembling aspen, ironwood, green ash, hemlock and balsam fir.

Table 5 summarizes the mean basal area by diameter class of the 11 study sites. These data more clearly separate the sites into age groups. Four sites, Etwell, Utterson, Swan Lake, and Indian River, contain more than 25% of the basal area in trees greater than 50 cm dbh. These are old growth stands, with Swan Lake and Utterson approaching over-maturity. In contrast, both Horn Lake and Musquash River have more than 65% of the basal area in the less than 30 cm diameter classes. These sites are relatively juvenile stands. The remaining study sites have a reasonable age class distribution.

These stand characteristics are quite typical of Ontario's hardwood forest. Essentially, all the hardwood forest has a history of harvesting under a variety of management regimes. These regimes may have changed several times in the woodlot's history. Typically, the hardwood forest was logged for it's white pine component through the 1800s and selectively cut for quality hardwood timber through the early to mid-1900s. Most recently, these stands have been managed for maple syrup production or as recreational property. Considerable effort has been made in the last decade to improve both the current quality and the future potential of Ontario's hardwood forest. This has been most successful to date on crown land.

Table 4
Study Site Stand Characteristics.

Study Site	Mean Basal Area m^2/ha	Mean Age yrs	MNR Site Class	% Sugar Maple
Magnetawan	30	70	3	87
Horn Lake	28	65	1	91
Cecebe Lake	28	55	1	74
Etwell	39	95	2	94
Point Ideal	28	105	1	54
Musquash River	41	75	2	30
Utterson	14	70	1	50
Swan Lake	25	120	2	67
Woodview	17	75	3	87
Indian River	25	85	1	97
Thunder Bay	34	115	2	83

- basal area is mean of 5 prism sweeps in and around the study plot.
- mean age estimated from increment cores collected at dbh from 6 co-dominant trees adjacent to the study plot.
- MNR site class based on height over age curves, after Plonski (1974)[87], site class 1 is best.

Table 5
Basal Area of the Study Sites by Diameter Class.

Study Site	% of Basal Area by dbh Class (cm) <10	10-20	21-30	31-40	41-50	>50
Magnetawan	10	26	19	29	13	3
Horn Lake	6	27	33	24	9	0
Cecebe Lake	0	29	29	32	8	0
Etwell	3	9	15	21	24	27
Point Ideal	11	18	29	25	7	11
Musquash R.	3	32	35	15	12	3
Utterson	4	12	15	8	19	42
Swan Lake	11	11	4	7	32	36
Woodview	9	22	13	39	17	0
Indian R.	3	7	3	33	27	27
Thunder Bay	0	25	23	38	13	3

9.3 Soil Classification

A soil pit was dug in an undisturbed area adjacent to the permanent observation plot at each of the 11 study sites. All pits were situated in mid to upper slopes and in well drained positions. Site locations were identified by UTM co-ordinates and a sketch map was prepared indicating pit locations relative to permanent local features and to the tree plot. The site was described according to the guidelines prescribed by the Ontario Institute of Pedology.[84]

At each site, a pit approximately 1 m by 1 m was dug to a depth sufficient to permit sampling of the C horizon or parent material. Soil profiles were described and classified according to the system of soil classification of Canada.[2] The soil pit was photographed and a sketch of one of the pit faces was drawn to illustrate soil horizon boundaries, stones, roots, and sample points. Beginning at the deepest horizon, 1 kg samples were obtained in duplicate from two sides of the pit. The samples were placed in numbered plastic bags and returned to the Phytotoxicology laboratory in Toronto for processing. Samples were air-dried, disaggregated, ground and sieved to two size fractions (10 and 45 mesh) and forwarded to the MOE laboratory for analysis. The following analyses were performed on each sample: pH (water and calcium chloride); exchangeable calcium (Ca), magnesium (Mg), potassium (K), and aluminum (Al); cation exchange capacity (CEC); pyrophosphate and dithionite extractable iron (Fe) and Al; organic carbon; total carbonates; total nitrogen (N); extractable Al and sulphate; total copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) and texture. Detailed methodology is outlined in the APIOS procedures manual.[45]

Table 6 lists the soil classification for the 11 study sites. The eight sites in Muskoka were naturally acidic podzol soils. The mineral soil pH at these sites ranged from 4.7 to 5.2. In contrast, the two Peterborough sites and the one site near Thunder Bay were neutral to slightly alkali brunisol soils.

Table 7 summarizes some of the soil pit analysis results for the B horizon at each study site. The B horizon is where most of the tree roots are located and where the tree obtains the bulk of it's required nutrients. Soils in Muskoka have developed on coarse textured glacial till material. The major rooting zone maximum depth varied from 40 cm at Swan Lake to 65 cm at Horn Lake. Bedrock outcrops were common at all of the study sites, indicating (generally) the presence of shallow soils. Soil profiles consisted of a thin (less than 10 cm) surface horizon (Ah) rich in organic material and underlain by well defined mineral B and C horizons. Earthworms were absent in these profiles because of the naturally acidic nature of the soil. Hence, mixing of organic matter into the mineral horizons was minimal. The soil profiles exhibited subsurface horizons (Bf, Bfh) enriched with Fe and Al, as evidenced by their reddish colour. Boulders and stones were abundant throughout the profiles. No carbonates were detected in any of the Muskoka-area soil pits.

The Peterborough soils have developed from a calcareous parent material. The average B horizon soil pH from these sites was neutral to slightly alkali, ranging from 7.4 (Indian River) to 7.7 (Woodview). The soil profiles consisted of a well mixed surface horizon and subsurface horizons containing up to 5% carbon. There was considerably more clay within these soil profiles compared to the Muskoka soil, which is reflected in higher cation exchange and base saturation levels at the Peterborough plots.

Table 6
Soil Classification of the Study Sites.

Study Site	Soil Classification	Parent Material
Magnetawan	sombric ferro-humic podzol	gravelly till
Horn Lake	sombric humo-ferric podzol	compact till
Cecebe Lake	gleyed ferro-humic podzol	sandy till
Etwell	sombric ferro-humic podzol	till
Point Ideal	sombric ferro-humic podzol	stony till
Musquash River	sombric ferro-humic podzol	lacustrian sand
Utterson	gleyed ferro-humic podzol	compact till
Swan Lake	sombric ferro-humic podzol	stony till
Woodview	orthic melanic brunisol	calcareous glacial till
Indian River	orthic melanic brunisol	calcareous glacial till
Thunder Bay	gleyed eutric brunisol	diabase colluvium

- classified according to the System of Soil Classification of Canada (1978).[2]

Table 7
Selected Rooting Zone Characteristics.

Study Site	Depth cm	pH	% sand	% clay	C.E.C. meq/100g	B.S. %	T.I.C. %	Al ppm
Magnetawan	50	5.0	80	3	1.06	27	ND	12
Horn L	65	4.9	68	3	1.22	12	ND	22
Cecebe L	50	4.8	48	3	1.30	19	ND	21
Etwell	60	5.0	81	2	0.79	25	ND	14
Pt Ideal	50	5.2	61	4	1.56	40	ND	13
Musquash	55	4.7	88	5	1.98	14	ND	28
Utterson	45	5.0	74	6	1.60	35	ND	20
Swan L	40	4.5	64	8	1.69	29	ND	16
Woodview	35	7.7	64	14	12.50	100	0.16	ND
Indian R	65	7.4	49	18	10.76	100	0.02	0.3
Thunder B.	57	6.6	50	9	6.62	99	0.07	0.1

- rooting zone is the B horizon.
- pH is in water.
- C.E.C - Cation Exchange Capacity.
- B.S - Base Saturation.
- T.I.C. - Total Inorganic Carbon.
- Al is plant available Al, i.e., water extractable.

The Thunder Bay soil was developed from a nutrient-rich diabase parent material. At pH 6.6, the soil was slightly acidic. The study site is positioned along the edge of a scree slope, therefore the soil has been subjected to additional gravitational processes during it's development. Lateral flow of ground water has resulted in gleyed soil conditions. Horizons are not well developed in the profile, probably due to the disruption of pedogenic process by colluvial deposits.

9.3.1 Soil Sensitivity to Acidic Deposition

It is generally accepted that acidic deposition can alter soil chemistry and potentially reduce forest vigour and productivity by two processes: 1) nutrient base cations may be leached out of the soil and become unavailable for plant uptake; and 2) acidic deposition may increase the availability of toxic elements.

The leaching of nutrient cations from soil (or the reduction of soil base saturation) is a natural process that occurs in humid forests. Soil acidification results from the replacement of Ca, Mg, Na, and K by hydrogen and Al on soil particles. A number of models have been developed that attempt to predict the degree of soil acidification if deposition rates and soil conditions are known. To date, under natural field conditions, there is no conclusive evidence that nutrient leaching is actually being accelerated by acidic deposition. Changes in soil chemistry have been simulated in laboratory experiments using soil columns and acidic treatments, but these controlled conditions cannot duplicate natural soil processes.

Two types of leaching systems have been identified: a bicarbonate/weak acid system and a sulphate/nitrate system. A shift occurs from the bicarbonate/weak acid system to the sulphate/nitrate system as soils acidify and become saturated with nitrate and sulphate. Eventually, nitrate and sulphate anions associated with nutrient base cations will begin to leach from the soil profile.

As soils acidify, some elements become more soluble, therefore increasing their plant-availability. Of the many trace elements in soil, Al has received the most attention with respect to forest decline. Scientists generally agree that Al is toxic to tree roots, but the level at which damage occurs for different species is still under investigation.

Soils vary in their ability to buffer acidity. Various soil constituents contribute to buffering capacity. Soils with pH values greater than 6.5 are in the carbonate buffering range. Soils with pH values between 5.0 and 6.5 are in the silicate buffering range whereby weathering offsets changes in soil solution pH. Soils with pH values between 4.2 and 5.0 are in the cation exchange buffering range where clay particles provide active cation exchange sites. Soils with pH values below 4.2 are buffered by Al hydroxides.[107] The soil from the Muskoka study sites lie primarily within the Al and cation exchange buffering range. Due to the coarse texture of these soils, the main source of cation exchange capacity would be organic colloids, the majority of which are located in the thin surface horizons above the active rooting zone. Levels of available Al are moderately high in the rooting zone of the Muskoka soils, reaching 33 parts per million (ppm) in the B horizon at Musquash River and 34 ppm at Cecebe Lake (the mean levels are 28 ppm and 21 ppm respectively). In contrast, the soil at the Peterborough and Thunder Bay-area study sites are largely within the carbonate buffering

range. Carbonates are associated with soils that are less sensitive to acidic deposition because carbonates neutralize incoming acidity and maintain pH values at levels that prevent Al from becoming soluble. The available Al concentration in the carbonate-rich Peterborough and Thunder Bay soils did not exceed 0.3 ppm, whereas the carbonate-poor Muskoka sites averaged from 12 to 28 ppm available Al, with higher concentrations encountered adjacent to the sample trees at a few sites.

Levels of extractable sulphate may provide a relative indication of the potential for base elements to associate with the sulphate anion and leach from the soil profile. Extractable sulphate levels tend to be higher in the Muskoka soils. In the mineral horizons of these podzolic soils, anion retention is great and if the soil becomes saturated with sulphate or nitrate, leaching of these anions will occur.

Attempts have been made to rate soil sensitivity to acidic deposition based on soil classification. Podzolic soils contain the lowest amount of bases and are the most susceptible to base element deficiencies and Al toxicity.[11] All eight of the Muskoka study sites have podzolic soils, and therefore are potentially sensitive to nutrient element deficiencies and Al toxicity as a result of acidic deposition. In contrast, both of the Peterborough sites and the Thunder Bay study site have brunisolic soils, which may be less sensitive to nutrient leaching but possibly more sensitive to changes in soil pH. Soil resampling work in Ontario found that podzolic soils with low pH in the Parry Sound area were not pH-altered by acidic deposition over an 18 year period from 1960 to 1978, whereas a brunisolic soil with an intermediate pH became more acidic.[63] However, soil resampling in Sweden, where the soils are very similar to the acidic podzols encountered in Muskoka, detected a drop in pH of up to one unit over a 56 year period.[7]

Soil sensitivity to acidic precipitation also can be estimated by the product of cation exchange capacity and base saturation, or base content.[114] In this system, sensitive soils are defined as having less than 6 milliequivalents (meq) exchangeable bases per 100 g of soil. Moderately sensitive soils have between 6 and 15 meq/100 g, and non-sensitive soils have greater than 15 meq/100 g. Table 8 summarizes the base content calculations for the 11 study sites and ranks them in increasing order of soil sensitivity to acidic precipitation. The data used to calculate the base content are from the weighted averages (by depth) of the A and B horizons and therefore they will not correlate with the data summarized in Table 7, which is B horizon data only. Woodview has 15.5 meq/100 g base content in the rooting zone and therefore is classified as non-sensitive. The Thunder Bay and Indian River sites have base contents of 14.7 and 14.5 meq/100 g respectively, and therefore just fall into the moderately sensitive category. By comparison, all of the Muskoka study sites have soil that is very sensitive to the effects of acidic deposition. Of this sensitive group, Point Ideal is the "best buffered" with a base content of 2.5 meq/100 g (although this is still very sensitive), and Cecebe Lake is the "least buffered", or most sensitive, with a base content of only 0.5 meq/100 g.

Table 8
Relative Soil Sensitivity to Acidification.

Study Site	Base Content meg/100 g	Sensitivity Ranking
Woodview	15.5	non-sensitive
Thunder Bay	14.7	moderately sensitive
Indian River	14.5	moderately sensitive
Point Ideal	2.5	sensitive
Utterson	2.3	sensitive
Musquash River	1.6	sensitive
Horn Lake	1.3	sensitive
Magnetawan	1.3	sensitive
Etwell	1.0	sensitive
Swan Lake	0.9	sensitive
Cecebe Lake	0.5	sensitive

- soil data from the depth weighted A and B horizon, not directly comparable to Table 7.
- base content sensitivity rating after Wang and Coote (1981).[114]
- study sites listed in order of increasing sensitivity.

9.4 Tree Condition Assessment

Regardless of the cause(s) of forest decline, a system of tree condition assessment is required to quantify the severity of the problem between regions and across time. Most tree rating systems are subjective and the assessment parameters are broad. A common approach is to categorize the degree of crown defoliation; e.g., <10%, 11%-25%, 26%-50% etc. Another frequently used concept is to stratify tree condition into a gradient of 1 to 5 or 1 to 10, usually with the lowest number equivalent to a tree with no symptoms and the highest number representing a dead tree. These systems are mostly qualitative, nondescriptive and have relatively poor resolution.

When the decision was made to initiate deciduous tree decline studies in Ontario in 1984, it was imperative that a tree rating system be developed that was quantitative, reproducible, and had a narrow confidence interval across a large gradient, so that subtle differences could be detected with time and between regions in the province.

In Ontario the symptoms that are most often observed in declining sugar maple tress are dieback of the fine branch structure, pale green or chlorotic foliage, and undersized leaves. These three descriptive crown parameters were individually assessed and combined in a weighted formula yielding a numerical Decline Index (DI) value ranging from 0 (a healthy tree with no symptoms) to 100 (a dead tree). The DI formula is:

$$DI = DB + (A \times UL) + (A \times ST) + (A \times SL/2)$$

where
DI = decline index
DB = per cent dead branches
UL = per cent undersized leaves
ST = per cent strong chlorosis
SL = per cent slight chlorosis
A = (100 - DB)/400

Laminated field assessment templates were prepared that illustrate a series of deciduous tree crown silhouettes in 10% gradients (0% full crown, 10% branch dieback ... 90% branch dieback, 100% dead tree). On the reverse side of the template are three series of six colour chips representing the range of foliar colour for sugar maple in Ontario. One series represents normal green foliage, another pale green or slightly chlorotic foliage, and the third illustrates the colour range considered to be significantly chlorotic. Using the templates, the percentage of dead branches, off colour foliage and small leaves are each estimated to 10%. The field data are transcribed to a spreadsheet and the DI is calculated to the nearest whole number.

The foliar parameters in the DI formula are weighted proportional to the live crown. Therefore trees with a relatively low percentage of branch dieback can have an elevated DI if a significant percentage of the living crown is off-colour and the foliage is small. This is important because foliar abnormalities may be an early warning of impending crown dieback and foliar characteristics change much more rapidly than branch structure.

In a series of tests conducted on the DI methodology it was determined that a paired assessment (two people jointly evaluating each tree) resulted in a slightly narrower confidence interval.[76] For example, a tree with a mean DI of 8 had a 99% confidence interval of 2.2 (i.e., DI = 8 +/- 2.2, 99 times out of 100) when repeatedly assessed by single evaluators. The 99% confidence interval fell to 1.8 when paired assessment was used. The coefficient of variation was inversely related to DI. This is not surprising because the proportional difference in the DI of a tree between evaluations is greater with healthier trees relative to trees in a more advanced stage of decline. For example, a healthy tree with a mean DI of 4 may have a range from 2 to 6, whereas a declining tree with a mean DI of 40 may have range from 35 to 45. Proportionately, the variation about the mean is much larger for the healthier tree than the declining tree, even though the absolute difference in DI is less.

9.4.1 Annual Decline Index Trends

Decline condition assessments of all trees in the 11 study plots were conducted in the last week of July and the first week in August annually from 1984 to 1990 (8 plots only in 1984). Annual tree assessment was suspended in 1991 pending the decision regarding the future use of the study sites. Seven consecutive years of assessment data are summarized in Table 9. These data indicate that the study plots represented a range of tree decline. The Point Ideal and Indian River plots consistently had the lowest mean DI (lowest incidence of decline). In contrast, Magnetawan consistently had the highest DI. The remaining plots exhibited light to moderate decline symptomatology throughout the observation period. Listed in order of highest mean DI (worst decline) to lowest mean DI (least decline) over the seven year assessment period the study sites rank as follows: Magnetawan - 38, Etwell - 28, Musquash River - 24, Cecebe Lake - 23, Woodview - 21, Horn Lake/Swan Lake - 17, Utterson/Thunder Bay - 13, and Point Ideal/Indian River - 10.

Based on the regional mean data for the first three years of the study, there was a trend towards an improvement in tree condition in all three study areas. The improvement was most pronounced in Thunder Bay, where the mean DI fell from 17 in 1984 to 6 in 1986. Although the trend was towards tree improvement in the first three years, the apparent change in the DI for the Muskoka sites was not significantly different. The improvement trend continued through 1987 in both Peterborough and Muskoka; however, the Thunder Bay site deteriorated significantly in this year. The deterioration in tree condition in Thunder Bay (DI was 6 in 1986 vs. 27 in 1987) was a result of a dramatic increase in the percentage of foliar chlorosis and small leaf size and not a result of an increase in branch dieback. An abrupt change in foliar characteristics also was primarily responsible for the dramatic rise in mean DI in both Muskoka and Peterborough in 1988. Tree condition deteriorated marginally in Peterborough in 1989, but improved in Muskoka and Thunder Bay.

Table 9
Mean Plot Decline Index: 1984 to 1990.

Study Site	1984	1985	1986	1987	1988	1989	1990	LSD	<p
Magnetawan	36	35	34	34	56	46	28	5	.05
Horn Lake	12	14	18	14	22	26	17	4	.01
Cecebe Lake	32	28	30	29	45	34	26	8	.05
Etwell	26	17	18	21	57	30	28	6	.01
Point Ideal	15	6	12	7	12	9	12	2	.01
Utterson	16	13	15	na	13	13	6	2	.01
Musquash River	21	22	26	22	na	29	26	3	.01
Swan Lake	ne	15	21	14	26	16	13	6	.01
Muskoka Mean	23	19	22	20	33	25	18	3	.01
Woodview	ne	22	19	14	26	25	20	3	.01
Indian River	ne	5	5	8	10	18	16	2	.01
Peterborough Mean	nc	14	12	11	18	22	18	2	.01
Thunder Bay	17	7	6	27	15	9	9	4	.01

LSD - (Fisher's) Least Significant Difference (any one year must be different from another year by at least this much for the difference between years to be statistically significant).
na - not assessed, defoliated by Forest Tent Caterpillar.
ne - not established.
nc - not calculated.
<p - statistical significance.

Forest tent caterpillar populations were very high throughout the Muskoka area in 1987 and particularly in 1988. All of the Muskoka study plots were defoliated to varying degrees. Forest tent caterpillar feeding occurs early in the growing season. By the time the tree condition assessment was conducted in mid-summer the trees at most sites had recovered sufficiently to permit evaluation (although the increase in DI in 1988 was driven primarily by foliar characteristics, which undoubtably were partially related to defoliation stress). However, tree evaluation was not conducted at Utterson in 1987 and Musquash River in 1988 because these two plots were defoliated too severely to conduct reliable tree condition assessment. Overall, tree condition improved in 1989 and again (marginally) in 1990.

9.4.2 Decline Index Relationships

There was no relationship between mean DI of each study site and stand stocking, basal area, total plot biomass, aspect, topography or soil physical characteristics. There was a tendency towards higher mean plot DI with poorer site class. The MNR identifies three basic site classes for tolerant hardwoods; 1 is best, 2 is intermediate, and 3 is poorest.[87] These site classes are based on tree "height-over-age" curves. Although these site class curves were not developed for management of uneven aged stands, they do provide a practical basis for comparison. The five site class 1 study plots had a mean DI of 16 from 1984 to 1987 (this four year period was chosen as the time frame for use with the DI relationships because it corresponded to the least annual variability). The four site class 2 study plots had a mean DI of 19 in the same period. The remaining two study plots were site class 3 and had a mean DI of 28. The difference in mean DI between site classes 1 and 2 was not statistically significant (using a t test). However, the mean DI for the site class 3 plots was significantly different than both the site class 1 and 2 plots (1 vs. 3: $t=3.26$, $p<0.01$; 2 vs. 3: $t=3.06$, $p<0.01$). These data imply that tree decline symptoms were more frequent and more severe on poorer sites.

Table 10 summarizes the mean DI for each plot by tree diameter class for the period 1984 to 1987. The DI tended to be higher in the largest and smallest diameter classes. The younger trees would be suppressed, and therefore more likely to exhibit decline symptoms than the co-dominant and dominant trees in the stand, which should be the most vigorous. Similarly, the oldest trees would be less vigorous and possibly predisposed to decline because of the pathological and physiological stresses associated with overmaturity. With all the data combined, the DI was positively and significantly related to tree diameter at breast height (dbh) ($f=8.25$, $p<0.01$) and can be described with the regression line equation;

$$\log DI = 0.081 \times \log dbh + 2.946$$

Table 10
Mean Study Site Decline Index by Diameter Class.

Study Site	Mean Decline Index by Diameter Class (cm) 10-15	16-20	21-25	26-30	31-35	>35
Magnetawan	32	20	29	27	37	35
Horn Lake	16	21	15	26	33	13
Cecebe Lake	26	25	17	29	13	38
Etwell	3	8	22	13	35	28
Utterson	16	12	9	21	27	23
Musquash R	16	20	26	26	22	32
Point Ideal	10	12	19	17	23	19
Swan Lake	21	17	16	20	19	25
Muskoka Mean	18	17	19	22	26	27
Woodview	14	13	16	24	22	22
Indian R	16	3	6	4	6	8
Peterborough Mean	15	8	11	14	14	15
Thunder Bay	19	25	31	31	28	26
Mean All Sites	17	16	19	22	24	24

- Decline Index Values are mean of 1984-1987 data.
- Diameter measured at 1.3 m (dbh).
- *log Decline Index = 0.081 X log dbh + 2.946 ($p<0.01$).*

This relationship was more pronounced at the Muskoka study sites than Peterborough, and least consistent at Thunder Bay. None-the-less, when all trees from all three study areas are considered, these data suggest that (generally) tree age was a predispositional factor to decline.

About one half of the trees in the study plots had at least one defect or wound. The frequency of common defects observed on the study trees is summarized in Table 11. Frost cracks were the most common defect, occurring on just over 37% of the trees. The next most common defect was tap hole wounds. These were observed on just over 30% of the trees, reflecting the current and historical use of some of the stands for maple syrup production.

Table 11 also lists the results of t tests to determine if the difference in mean DI between trees with and without various defects is statistically significant. There was no significant differences in mean DI between trees with and without frost cracks, maple borer and bark slough. On average, trees that had been tapped for maple syrup production, had fungal fruiting bodies, cankers, broken leaders and "other wounds" (see Table 11) were statistically more likely to have a higher DI.

Although it appears that the frequency of certain defects and wounds may be related to poorer tree condition, this relationship may not be as straightforward as it seems. Older trees tend to accumulate wounds of this nature. It has been established that DI increased with tree age (as estimated by dbh). Therefore the wound/DI relationship may be skewed by the age/DI relationship, or visa versa. This could be particularly true of the tap hole wounds, as generally only the larger trees are tapped. Also, the use of group means may be of limited practical value because the wound groups were not mutually exclusive (i.e., trees that did not have frost cracks, for example, may or may not have had other wounds).

Regardless, these data illustrated that the presence of many common defects and wounds was consistently associated with trees in poorer condition. Unquestionably, the stress associated with wound physiology exacerbates tree decline.

9.5 Chemical Analyses

Six additional trees were selected at each of the 11 study sites. These trees, located adjacent to the permanent observation plots, were intensively sampled. They were dominant or co-dominant trees and were selected to represent a gradient of decline conditions evident in the stand. Three trees were classified as healthy (DI <12) and three trees were rated as declining (DI >30). There were no causal factors apparent on the declining trees that could be associated with their deteriorated condition.

Table 11
Mean Decline Index of Trees With and Without Defects.

Type of Defect	% of Trees Affected	Mean Decline Index Defect	No Defect	p<
frost crack	37.1	16	15	ns
tap hole	30.1	18	11	.01
maple borer	27.3	15	15	ns
epicormic sprout	14.0	10	16	.01
bark slough	12.9	17	16	ns
canker	6.8	23	17	.01
broken leader	4.2	26	15	.01
fruit bodies	3.0	32	19	.01
other defect*	29.5	20	14	.01

* other defects include logging wounds, porcupine damage, scars from wire or rope, root damage on trails.

- Decline Index values are mean of 1984-1987 data.
- defect populations are not mutually exclusive.

ns - not significant, p>0.05.

9.5.1 Soil Chemistry

Triplicate soil samples were collected from within the drip line of the six sampled trees at each study site. The surface litter layer was scraped away and an Oakfield soil corer was used to extract composite soil plugs 0 to 30 cm in depth from the underlying mineral soil. The samples were collected in labelled plastic bags and placed in refrigerated storage. In preparation for chemical analysis the samples were air dried, sieved through a 2 mm screen and pulverized with mortar and pestle to pass through a 45-mesh sieve. The prepared samples were analyzed by ICAP or AAS for total concentrations of six macro-nutrients (Ca, K, Mg, N, P and S), six micro-nutrients (B, Cu, Fe, Mn, Mo and Zn) and nine other elements, mostly trace metals (Al, Cd, Cl, Cr, F, Na, Ni, Pb and V).

The data were aggregated by tree health status for each of the three study regions. A t test was used to identify statistically significant differences in soil chemistry between the healthy and declining tree populations from each region.

Table 12 summarizes the soil chemistry from the eight study plots in the Muskoka region. There were no significant differences in total soil macro-nutrient concentrations between healthy and declining trees in Muskoka. In fact, most of the elements tended to be marginally higher in soil collected from beneath declining trees.

Zinc was the only micro-nutrient that was found in significantly lower concentrations in soil from declining trees. The Zn levels from the Muskoka study plots were the lowest of the three study regions. Also, the mean soil Zn concentration associated with declining trees in Muskoka was only about one half that found beneath healthy sugar maple trees. Despite this discrepancy the Zn levels are within those reported in the literature. Therefore, Zn deficiency is not inciting tree decline in Muskoka, although it may be a contributing factor in the decline phenomenon.

Even though the total concentrations of many of the nutrient elements are relatively low compared to the other two study regions, the low soil pH (4.5 to 5.2) that is characteristic of the Muskoka sites, would tend to increase nutrient availability. The only other element determined to be significantly different was Pb, and it was marginally higher in soil collected from beneath declining trees.

Table 13 summarizes the soil chemistry from the two study plots in the Peterborough region. None of the soil nutrient concentrations were significantly lower in the declining tree population. In fact, three macro-nutrients (Ca, K and Mg) and three micro-nutrients (B, Fe and Mn) were present in significantly higher concentrations in soil from under declining trees.

In the Peterborough region Cr, F, Na and Ni were all detected in marginally higher (but statistically significant) concentrations in soil associated with declining trees. However, these elements were not causally related to tree decline as they are well within the range reported in the literature. Also, similar and much higher concentrations were encountered in soil from healthy trees in the Thunder Bay study plot. Soil total sulphur concentrations were not available for the Peterborough and Thunder Bay regions because these samples were destroyed in a laboratory accident.

Table 12
Mean Soil Chemical Concentrations of the Muskoka Study Sites.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro- Nutrients (%)					
Calcium	0.11	(.05)	0.12	(.05)	ns
Potassium	0.04	(.02)	0.05	(.02)	ns
Magnesium	0.14	(.08)	0.15	(.08)	ns
Nitrogen	0.28	(.12)	0.29	(.08)	ns
Phosphorous	0.05	(.03)	0.05	(.02)	ns
Sulphur	0.04	(.01)	0.04	(.01)	ns
Micro- Nutrients (ppm)					
Boron	2	(1)	3	(1)	.01
Copper	7	(5)	7	(3)	ns
Iron	19190	(5100)	21160	(7630)	ns
Manganese	144	(60)	173	(73)	.01
Molybdenum	1.9	(1.2)	2.6	(2.2)	.05
Zinc	33	(17)	17	(17)	.01
Other Elements (ppm)					
Aluminum	10800	(2990)	11590	(3793)	ns
Cadmium	0.5	(0.3)	0.5	(0.3)	ns
Chloride	140	(129)	110	(55)	ns
Chromium	17	(18)	13	(4)	ns
Fluoride	16	(9)	14	(7)	ns
Sodium	92	(52)	97	(54)	ns
Nickel	6	(4)	5	(3)	ns
Lead	11	(3)	10	(3)	.05
Vanadium	34	(15)	38	(22)	ns

* acid digest total ppm or % as indicated, air dry weight, mineral soil 0 to 30 cm depth.
- number of samples = 72.
ns - not significant (p>0.05).
SD - standard deviation.

Table 13
Mean Soil Chemical Concentrations of the Peterborough Study Sites.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	0.71	(.42)	2.21	(1.66)	.01
Potassium	0.08	(.02)	0.11	(.03)	.01
Magnesium	0.25	(.05)	0.33	(.04)	.01
Nitrogen	0.24	(.04)	0.20	(.05)	ns
Phosphorous	0.07	(.01)	0.08	(.01)	ns
Sulphur	na	(nc)	na	(nc)	nc
Micro-Nutrients (ppm)					
Boron	3	(0)	5	(1)	.01
Copper	9	(2)	10	(2)	ns
Iron	15750	(1920)	16330	(1940)	.05
Manganese	409	(135)	531	(118)	.05
Molybdenum	1	(0)	1	(0)	ns
Zinc	47	(6)	45	(5)	ns
Other Elements (ppm)					
Aluminum	10360	(1703)	11270	(1750)	ns
Cadmium	0.2	(0)	0.2	(.04)	ns
Chloride	225	(50)	200	(75)	ns
Chromium	15	(2)	18	(2)	.01
Fluoride	32	(13)	59	(10)	.01
Sodium	120	(30)	159	(15)	.01
Nickel	7	(1)	8	(1)	.05
Lead	11	(2)	11	(2)	ns
Vanadium	28	(3)	29	(3)	ns

* acid digest total ppm or % as indicated, air dry weight, mineral soil 0 to 30 cm depth.
- number of samples n = 18.
ns - not significant (p>0.05).
na - not available.
nc - not calculated.
SD - standard deviation.

Table 14 summarizes the soil chemistry from the Thunder Bay study site. In contrast to the Peterborough and Muskoka soil data, all of the macro and micro-nutrient concentrations were significantly lower in soil collected from beneath declining trees in Thunder Bay. In addition, seven of the nine trace elements also were present in significantly lower levels around declining trees in Thunder Bay.

The Thunder Bay soil characteristics are quite similar to Peterborough. The K, Mg, B, Cu, Fe Mo and Zn soil concentrations from declining trees in Thunder Bay are very comparable to those from healthy trees in Peterborough; therefore, the differences in these elements in Thunder Bay are unlikely to be causally associated with tree decline at this site. However, the Ca, N, P and Mn concentrations of soil from beneath declining trees in Thunder Bay were considerably less than corresponding soil from healthy trees from both Thunder Bay and Peterborough.

These data indicate that tree decline in Peterborough is not likely associated with soil nutrient deficiencies or trace element toxicity. Soil Zn deficiencies may be exacerbating tree decline in Muskoka. The soil at the Thunder Bay study site may be inherently deficient in Ca, N, P and Mn. Total soil chemical concentrations are generally considered to be an unreliable measure of site nutrient status because of the various soil physiological parameters that affect nutrient availability. Soil chemistry should be used in conjunction with foliar chemistry to achieve a more accurate assessment of the site nutrient regime.

9.5.2 Foliar Chemistry

Nitrogen, Ca, K, Mg P and S are required by trees in relatively large concentrations; hence, they are often referred to as macro-nutrients. In contrast B, Cu, Fe, Mn, Mo and Zn are known as micro-nutrients because they are utilized in small amounts, even though they are essential for plant growth. Nitrogen is probably the most important element for forest tree growth, whereas P, K, and Ca in addition to N, are the nutrient elements which are most often limiting.[100] It is known that mycorrhizae have the ability to supply P, and to a lesser extent N in soil where these elements are in relatively low concentrations.[48, 102] Although it is assumed that mycorrhizae assist the feeder roots in extracting soluble soil elements, the exact mechanisms involved in this symbiotic relationship are not fully understood.

Because of the passive nature in which soil nutrient availability is utilized, trees tend to take up what they can and not necessarily what they need.[6] This can lead to supra-optimal foliar concentrations, which are more than the tree needs or can use. Supra-optimal concentrations of some elements may lead to nutrient imbalance through elemental antagonism or may even be phytotoxic. Also, foliar chemistry will vary considerably from site to site, between species, between trees of the same species, through the growing season, and crown position. Despite this well documented chemical variability, it is generally accepted that foliar chemistry is a relative indicator of site quality.

Table 14
Mean Soil Chemical Concentrations of the Thunder Bay Study Site.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	0.63	(.08)	0.30	(.07)	.01
Potassium	0.17	(.01)	0.06	(.01)	.01
Magnesium	0.61	(.08)	0.27	(.10)	.01
Nitrogen	0.36	(.03)	0.15	(.03)	.01
Phosphorous	0.09	(.01)	0.03	(.01)	.01
Sulphur	na	(nc)	na	(nc)	nc
Micro-Nutrients (ppm)					
Boron	7	(1)	4	(1)	.01
Copper	78	(23)	10	(4)	.01
Iron	33033	(4947)	20330	(4714)	.01
Manganese	780	(188)	160	(49)	.01
Molybdenum	2	(.2)	1	(0)	.01
Zinc	150	(42)	83	(22)	.01
Other Elements (ppm)					
Aluminum	na	(nc)	na	(nc)	nc
Cadmium	1	(.3)	0.3	(.09)	.01
Chloride	310	(20)	130	(45)	.01
Chromium	41	(5)	27	(4)	.01
Fluoride	27	(8)	3	(1)	.01
Sodium	420	(28)	260	(81)	.01
Nickel	33	(7)	15	(5)	.01
Lead	20	(3)	7	(2)	.01
Vanadium	86	(10)	80	(6)	nc

* acid digest total ppm or % as indicated, air dry weight, mineral soil 0 to 30 cm depth.
- number of samples = 9.
na -not available.
nc - not calculated.
ns - not significant (p>0.05).
SD - standard deviation.

Foliage was collected from the six trees selected for intensive sampling at each of the 11 study sites. The foliar samples were obtained in triplicate from the terminal portions of branches from the bottom 1/4 of the crown in the first week of August. The samples were placed in labelled plastic bags and stored under refrigeration. The samples were processed not-washed and oven-dried and analyzed by ICAP or AAS for the same 21 elements as the soil samples.

The data were pooled to reflect mean foliar chemical concentrations for healthy and declining sugar maple for the three study regions. Tables 15, 16 and 17 summarize the foliar chemistry for the Thunder Bay, Muskoka and Peterborough regions respectively.

The Thunder Bay soil chemistry suggested that substantial nutrient deficiencies exist, as all of the nutrient concentrations were significantly lower in declining trees. However, only K, S and Mo are consistently lower in the foliage of declining trees. If localized soil nutrient availability is a problem at Thunder Bay the trees are able to compensate, as the foliar chemistry (with the exception of K, S and Mo) does not implicate a nutrient deficiency. Declining Thunder Bay sugar maple foliage averaged 0.88% K. This is higher than healthy trees at both Muskoka and Peterborough and compares favourably with foliar K concentrations for healthy trees from Quebec and the NE US (see Table 18). Similarly, foliar Mo levels from declining trees in Thunder Bay are higher than those encountered in healthy sugar maple elsewhere in Ontario. Therefore K and Mo deficiencies are unlikely to be causal factors in the decline observed at the Thunder Bay study plot.

Sulphur is the only nutrient that may be in critical supply in Thunder Bay and therefore may have a mechanistic role in the decline in this area. Whereas the healthy trees at Thunder Bay have foliar S levels that were comparable to healthy trees in Muskoka and Peterborough, the declining trees at Thunder Bay consistently had the lowest S concentrations.

Although some statistically significant differences of foliar trace element chemistry occurred between healthy and declining trees in Thunder Bay, all the levels were well within those reported in the literature and therefore phytotoxicity is not implicated in the decline.

Foliar K and P concentrations were significantly lower in declining trees in Muskoka. Even though the absolute difference between the healthy and declining trees for these two elements was marginal it was still statistically significant. There was no corresponding reduction in soil K and P levels at Muskoka. Both the K and P foliar levels of declining trees in Muskoka were lower than concentrations detected in sugar maple from the other two Ontario study areas. Also, the levels of these macro-nutrients from declining Muskoka trees were within the foliar deficiency range reported in Quebec and the NE US (see Table 18). Therefore, the possibility exists that K and/or P deficiencies are contributing to tree decline in Muskoka. None of the micro-nutrient foliar concentrations were significantly different in the Muskoka trees. Similarly, all of the trace elements were well within reported literature values.

Table 15
Mean Sugar Maple Foliar Chemical Concentrations at the Thunder Bay Study Site.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	1.03	(.13)	0.88	(.24)	ns
Potassium	1.31	(.07)	0.88	(.10)	.01
Magnesium	0.18	(.02)	0.23	(.05)	.05
Nitrogen	1.54	(.18)	2.10	(.41)	.01
Phosphorous	0.19	(.03)	0.40	(.07)	.01
Sulphur	0.18	(.02)	0.13	(.03)	.01
Micro-Nutrients (ppm)					
Boron	53	(5)	70	(15)	.01
Copper	7	(1)	10	(1)	.01
Iron	53	(6)	52	(4)	ns
Manganese	201	(22)	362	(97)	.01
Molybdenum	0.8	(.1)	0.6	(.1)	.01
Zinc	21	(3)	31	(7)	.01
Other Elements (ppm)					
Aluminum	30	(3)	21	(3)	.01
Cadmium	0.2	(.03)	0.3	(.1)	.01
Chloride	500	(100)	100	(0)	.01
Chromium	1	(.4)	2	(.6)	.01
Fluoride	1	(.4)	<1	(nc)	ns
Sodium	10	(1)	10	(1)	ns
Nickel	<1	(nc)	<1	(nc)	ns
Lead	1	(.8)	1	(.5)	ns
Vanadium	<1	(nc)	<1	(nc)	ns

* acid digest total ppm or % as indicated, oven dry weight.
- number of samples = 9.
nc - not calculated.
ns - not significant (p>0.05).
SD - standard deviation.

Table 16
Mean Sugar Maple Foliar Chemical Concentrations at the Muskoka Study Sites.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	0.95	(.25)	0.86	(.32)	ns
Potassium	0.77	(.17)	0.72	(.11)	.05
Magnesium	0.13	(.05)	0.14	(.04)	ns
Nitrogen	1.94	(.26)	1.96	(.27)	ns
Phosphorous	0.13	(.03)	0.12	(.01)	.01
Sulphur	0.17	(.03)	0.17	(.04)	ns
Micro-Nutrients (ppm)					
Boron	54	(9)	57	(10)	ns
Copper	7	(1)	7	(2)	ns
Iron	74	(13)	71	(14)	ns
Manganese	1485	(475)	1676	(822)	ns
Molybdenum	<0.5	(nc)	<0.5	(nc)	ns
Zinc	33	(7)	31	(7)	ns
Other Elements (ppm)					
Aluminum	39	(6)	39	(6)	ns
Cadmium	0.6	(.2)	0.5	(.2)	.01
Chloride	240	(83)	260	(109)	.05
Chromium	2	(.7)	2	(.6)	ns
Fluoride	<1	(nc)	<1	(nc)	ns
Sodium	<10	(nc)	<10	(nc)	ns
Nickel	2	(.7)	2	(.4)	ns
Lead	<1	(nc)	<1	(nc)	ns
Vanadium	<1	(nc)	<1	(nc)	ns

* acid digest total ppm or % as indicated, oven dry weight.
- number of samples = 72.
nc - not calculated.
ns - not significant (p>0.05).
SD - standard deviation.

Table 17
Mean Sugar Maple Foliar Chemical Concentrations at the Peterborough Study Sites.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	1.26	(.27)	0.83	(.44)	.01
Potassium	0.77	(.07)	0.76	(.12)	ns
Magnesium	0.14	(.02)	0.17	(.22)	.01
Nitrogen	1.44	(.21)	1.47	(.19)	ns
Phosphorous	0.17	(.05)	0.19	(.05)	ns
Sulphur	0.15	(.02)	0.16	(.03)	ns
Micro-Nutrients (ppm)					
Boron	45	(6)	45	(5)	ns
Copper	6	(1)	6	(1)	ns
Iron	123	(9)	67	(14)	.01
Manganese	81	(21)	105	(33)	.01
Molybdenum	<0.5	(nc)	<0.5	(nc)	ns
Zinc	12	(1)	10	(2)	.01
Other Elements (ppm)					
Aluminum	41	(7)	52	(10)	.01
Cadmium	0.1	(.03)	0.1	(.01)	ns
Chloride	300	(100)	500	(250)	.01
Chromium	1	(.3)	1	(.4)	ns
Fluoride	<1	(nc)	<1	(nc)	ns
Sodium	10	(1)	11	(2)	ns
Nickel	2	(6)	1	(1)	ns
Lead	<1	(nc)	<1	(nc)	ns
Vanadium	<1	(nc)	<1	(nc)	ns

* acid digest total ppm or % as indicated, oven dry weight.
\- number of samples = 18.
nc - not calculated.
ns - not significant (p>0.05).
SD - standard deviation.

Table 18
Comparison of Sugar Maple Foliar Macro-Nutrient Concentrations from Quebec, NE U.S.A., and Ontario.

Element	Concentration (ppm - oven dry weight)						
	Quebec		NE U.S.A.		Ontario		
	Average	Deficient	Healthy	Declining	Thunder Bay	Muskoka	Peterborough
Nitrogen	2.19	1.50	1.95	1.63	1.54 (H)	1.94 (H)	1.44 (H)
Phosphorous	0.13	0.08	0.18	0.15	0.19 (H)	0.12 (D)	0.17 (H)
Potassium	0.70	0.60	0.89	0.72	0.88 (D)	0.72 (D)	0.76 (D)
Calcium	1.10	0.70	2.19	1.99	0.88 (D)	0.86 (D)	0.83 (D)
Magnesium	0.12	0.39	0.39	0.35	0.18 (H)	0.13 (H)	0.14 (H)

Quebec data from Gagnon et al. (1985).[42]
NE U.S.A. data from Dyer and Mader (1986).[19]
Ontario data from Tables 15, 16 and 17 are the lowest mean concentrations from each of the regions, the letter indicates a Healthy (H) or a Declining (D) tree group.

The Peterborough foliar chemistry revealed that declining trees had significantly lower Ca, Fe and Zn levels. Iron can be disregarded with respect to deficiency because both healthy and declining trees from Thunder Bay had lower concentrations. In contrast, both Ca and Zn were lower in declining Peterborough trees than trees from the other Ontario study areas. Also, declining Peterborough trees were encroaching on the Ca deficiency levels reported for Quebec and were well within the NE US deficiency range. However, the latter appears to be extremely liberal because the foliar levels for Quebec and all of the Ontario sites, regardless of tree condition, fall below the deficiency point. It is possible, though, that Ca and Zn deficiencies are exacerbating the decline observed in sugar maple in Peterborough. All of the other elements from the Peterborough-area trees were well within reported literature values.

Recent research in Quebec and Europe has suggested that even though individual nutrients may not be deficient, some elements may be present in imbalanced concentrations.[108] An over-abundance of one element, particularly Al, may impede the uptake of essential nutrients. Quebec researchers have developed molar ratios for Ca/Mg, Ca/K and Ca/Al to identify potentially antagonistic relationships. Table 19 summarizes these molar ratios in relation to healthy and declining foliar data from Ontario.

The Ca/Al ratios from all three study areas were above the 150 minimum suggested by the Quebec research. Similarly, the Muskoka ratios for Ca/Mg and Ca/K do not indicate a potential imbalance of these three nutrients, even though the foliar data (Table 16) suggested a possible K deficiency. The Ca/Mg ratio from Thunder Bay was consistent with the Quebec findings, but the Ca/K ratio suggested an imbalance, which was worse with the healthy trees. The Peterborough ratios were the most inconsistent when compared to the Quebec data.

The molar ratios calculated for the Ontario study sites were not consistent with regards to tree condition or between study areas. Foliar chemistry can vary widely across the geographic range of a tree species. Molar ratios may have greater diagnostic application if developed on a regional level, or on a soil-type specific basis.

9.5.3 Root Chemistry

In most plants, roots account for between 50% and 80% of the annual dry matter production.[12] In trees, carbon allocation to root growth is secondary only to foliage and new shoots.[47] When the tree is under stress primary carbon allocation shifts in favour of increased root production at the expense of all other plant requirements. This investment in root biomass is necessary because soil mineral nutrient concentrations are usually so low that absorption quickly depletes their availability in the immediate vicinity of the roots. Only through constant growth can the roots "mine" a sufficient volume of soil to meet the nutrient requirements of a growing tree. In a northern hardwood forest, one square metre of soil 10 cm deep has a cumulative fine-root length of approximately 25 km, which is a biomass of more than 7000 kg/ha.[123]

Table 19
Molar Ratios of Sugar Maple Foliage from the Three Ontario Study Regions.

Element	Min.	Max.	Molar Ratio Thunder Bay H	Thunder Bay D	Muskoka H	Muskoka D	Peterborough H	Peterborough D
Ca/Mg	2.5	8.0	5.7	3.8	7.3	6.1	9.0	10.8
Ca/K	1.0	2.0	0.8	1.0	1.2	1.2	1.6	2.4
Ca/Al	100-150	na	343	419	244	221	307	352

H - Healthy trees.
D - Declining trees.
na - not available.

Less than 10% of the root system expresses a geotropic response to grow downwards. The remaining 90% of the roots are plagiotropic and grow at any angle relative to local environmental conditions.[121] Roots are constantly and randomly growing and simply survive where the local conditions are favourable and die where they are not. Most of the root biomass grows essentially horizontal, sometimes as long as the tree is tall, although with sugar maple the main concentration of roots lies within the crown dripline.[21] Although sugar maple can be deep rooted on appropriate sites, most of the fine feeder root system exists in the top 5 to 10 cm of soil, or even into the humus layer.[10] Therefore, sugar maple is sensitive to drought, particularly on coarse-textured and very fine-textured soils and sites where the soil is very shallow.

Root tips 1 to 3 mm in diameter may elongate up to 1 m per year, although the average growth is usually much less.[48] Sugar maple fine root growth begins in the middle of March when the soil temperature reaches about 4^0 C and slows dramatically from the end of June through August, after which the growth rate increases again until the soil freezes.[81] This is opposite to the pattern of shoot growth and may be related to competition for photosynthate, inhibition (to roots) of high auxin concentrations produced by shoots, or periods of summer drought.

Roots are among the tree's most important organs, yet for obvious reasons, they are rarely sampled. Portions of the root system of four trees (two healthy and two declining) at each of the Woodview, Indian River, Swan Lake and Thunder Bay study sites were excavated so that tissue samples could be collected for chemical analysis and pathological examination. Two trees (one healthy and one declining) were selected for root sampling at the Magnetawan, Horn Lake, Cecebe Lake, Etwell, Musquash River and Point Ideal study sites. Roots were not excavated at the Utterson plot. Root excavation was conducted only on the trees from which foliar and soil samples had also been collected. Root samples were collected in triplicate from the end of excavated lateral roots from each of the sampled trees. The samples were separated into fine root (<2 mm diameter) and coarse root (>2 mm <1 cm) fractions. All samples were refrigerated in labelled plastic bags until processing for chemical analysis or pathological examination (pathological results are discussed in Section 9.7.1). The root samples were washed clean of visible soil then submerged in a warm water ultrasonic bath for 15 minutes to remove minute soil particles that may have adhered to the root epidermis. Chemical analysis was performed on an oven dry basis by ICP or AAS for the same 21 elements as the soil and foliage samples.

Chemical analysis was intended to determine what elements had been taken up and retained by the roots and not just what was simply adhering to the root epidermal layer, hence the vigorous washing procedure. The ultrasonic preparation may have been a little too rigorous and actually leached some of the more soluble elements from the root tissue. Therefore the root chemical concentrations presented here may be slightly conservative. This may have been more of a concern for the root samples from declining trees. These were observed to be consistently in poorer condition (i.e., fewer number of living root tips, lesser degree of fine branching, lower overall biomass, higher frequency of dead roots and sloughing cortex tissue).

The fine root chemical concentrations are summarized in Tables 20 (Muskoka), 21 (Peterborough) and 22 (Thunder Bay). A t test was used to identify statistically significant differences between healthy and declining trees.

At the Muskoka study sites there were no significant differences in micro-nutrient fine root concentrations between the healthy and declining trees. However, concentrations of the macronutrients Mg, N and P were significantly lower in roots from declining trees. The Mg and N levels may not be important because the foliar chemistry for these elements does not indicate a deficiency. In contrast, the significantly lower P concentrations in roots from declining trees are consistent with lower foliar levels and corroborate the possibility that P deficiency is a contributing factor to tree decline in the Muskoka area.

By comparison, root chemistry was much more variable in the Peterborough and Thunder Bay plots. Lower root S concentrations at Thunder Bay are consistent with the depressed foliar levels for this element. Similarly, the Zn concentrations of roots from Peterborough are the lowest of all the study areas and corroborate the possibility of a Zn deficiency contributing to tree decline in this region. The remainder of the nutrient differences are generally inconsistent with differences in foliar chemistry.

Differences in trace element root chemistry between healthy and declining trees were quite common in the Thunder Bay and Peterborough areas. However, the absolute differences are marginal or bear no logical relation to tree condition and are, therefore, not likely to be of any environmental significance.

Significant differences in the Muskoka tree root data were also detected for some of the trace elements. With the exception of Al, these elements are probably inconsequential because, like the Peterborough and Thunder Bay data, the absolute differences are small. In contrast, fine roots from declining trees in Muskoka averaged 3814 ppm Al, which is 63% higher than the 2341 ppm detected in roots from healthy trees. By comparison, the highest root Al levels were 1825 ppm in Peterborough and 1986 ppm in Thunder Bay, both from the healthy tree group. This suggests that root Al toxicity may be a contributing factor to tree decline in Muskoka. The relationship between Al and tree decline is discussed in more detail in Section 9.5.3.1.

The Al concentrations in the coarse root fraction were proportionately lower than the fine roots in all three study regions. Table 23 lists the average fine and coarse root Al levels for sugar maple trees in Muskoka, Peterborough and Thunder Bay. In Muskoka the average Al concentration in the coarse roots was 45% lower than in the fine roots (3078 ppm - fine vs. 1699 ppm - coarse) even though the distance along the root system between the two root fractions was generally considerably less than one metre. Even more dramatic reductions in Al concentrations between the two root size fractions were encountered in Peterborough and Thunder Bay.

Table 20
Mean Sugar Maple Fine Root Chemical Concentration of the Muskoka Study Sites.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	0.50	(.13)	0.44	(.18)	ns
Potassium	0.18	(.05)	0.19	(.04)	ns
Magnesium	0.08	(.01)	0.08	(.01)	ns
Nitrogen	0.84	(.27)	0.65	(.14)	.01
Phosphorous	0.07	(.03)	0.05	(.01)	.01
Sulphur	0.09	(.02)	0.08	(.02)	ns
Micro-Nutrients (ppm)					
Boron	16	(9)	13	(8)	ns
Copper	11	(6)	8	(3)	ns
Iron	827	(361)	801	(564)	ns
Manganese	289	(184)	202	(149)	ns
Molybdenum	<0.5	(nc)	<0.5	(nc)	nc
Zinc	69	(31)	55	(2)	ns
Other Elements (ppm)					
Aluminum	2341	(1177)	3814	(1175)	.01
Cadmium	1.3	(.4)	1.0	(.3)	.01
Chloride	<100	(nc)	<100	(nc)	ns
Chromium	3	(5)	2	(1)	ns
Fluoride	2	(2)	1	(.3)	.05
Sodium	38	(7)	56	(21)	.01
Nickel	6	(2)	8	(4)	.05
Lead	8	(7)	5	(6)	ns
Vanadium	2	(1)	3	(1)	.01

- data are acid digest total ppm or % as indicated, washed and oven dried, fine roots <2 mm diameter.
- number of samples = 24.

ns- not significant (p>0.05).
nc - not calculated (>50% of the data <analytical detection limit).
SD - standard deviation.

Table 21
Mean Sugar Maple Fine Root Chemical Concentration of the Peterborough Study Sites.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	1.32	(.37)	1.73	(.40)	.05
Potassium	0.27	(.11)	0.20	(.05)	.05
Magnesium	0.12	(.03)	0.14	(.03)	ns
Nitrogen	0.74	(.10)	0.63	(.10)	.01
Phosphorous	0.10	(.01)	0.12	(.03)	.05
Sulphur	0.08	(.02)	0.08	(.01)	ns
Micro-Nutrients (ppm)					
Boron	27	(7)	29	(4)	ns
Copper	20	(10)	12	(3)	.05
Iron	1838	(287)	1333	(398)	.01
Manganese	188	(41)	146	(29)	.01
Molybdenum	1	(.3)	1	(.2)	ns
Zinc	38	(10)	25	(6)	.01
Other Elements (ppm)					
Aluminum	1825	(228)	1612	(479)	.05
Cadmium	0.8	(.3)	0.5	(.1)	.01
Chloride	100	(0)	100	(0)	ns
Chromium	3	(.5)	4	(.7)	.01
Fluoride	7	(2)	11	(3)	.01
Sodium	44	(10)	41	(9)	ns
Nickel	4	(1)	3	(1)	.05
Lead	7	(1)	5	(1)	.01
Vanadium	6	(2)	9	(2)	.01

- data are acid digest total ppm or % as indicated, washed oven dried weight, fine roots <2 mm diameter.
- number of samples = 12.

ns - not significant (p>0.05)
SD - standard deviation.

Table 22
Mean Sugar Maple Fine Root Chemical Concentration of the Thunder Bay Study Site.

Element	Mean Concentration (SD)* Healthy Trees		Declining Trees		p<
Macro-Nutrients (%)					
Calcium	0.63	(.14)	0.73	(.05)	ns
Potassium	0.40	(.04)	0.42	(.01)	ns
Magnesium	0.09	(.01)	0.07	(.01)	.01
Nitrogen	0.91	(.04)	0.68	(.09)	.01
Phosphorous	0.12	(.01)	0.09	(.01)	.01
Sulphur	0.10	(.01)	0.08	(0)	.01
Micro-Nutrients (ppm)					
Boron	13	(2)	13	(2)	ns
Copper	32	(9)	10	(3)	.01
Iron	1407	(719)	247	(85)	.01
Manganese	137	(12)	167	(21)	.01
Molybdenum	1	(.1)	2	(.2)	.01
Zinc	9	(15)	66	(14)	.05
Other Elements (ppm)					
Aluminum	1986	(1162)	588	(784)	.05
Cadmium	1.7	(.4)	1.8	(.4)	ns
Chloride	200	(0)	200	(0)	ns
Chromium	3	(.9)	2	(.5)	.05
Fluoride	3	(.8)	1	(0)	.01
Sodium	53	(11)	52	(8)	ns
Nickel	6	(2)	2	(1)	.01
Lead	5	(0)	3	(1)	.01
Vanadium	4	(.9)	2	(1)	.01

- data are acid digest total ppm or % as indicated, washed oven dry weight, fine roots <2 mm diameter.
- number of samples = 6.

ns - not significant (p>0.05).
SD - standard deviation

Table 23
Mean Sugar Maple Fine and Coarse Root Aluminum Concentrations from the Three Study Regions.

Study Region	Soil pH[1]	Available Al[2]	Root Al Concentration[3] Fine Roots	Root Al Concentration[3] Coarse Roots
Thunder Bay	6.6	0.1	1287	536
Muskoka	4.9	18.0	3078	1699
Peterborough	7.6	0.2	1719	588

1 - B horizon, pH in water.
2 - ppm, water extractable.
3 - data are acid digested total ppm, washed oven dried weight, fine roots <2 mm diameter, coarse roots >2 mm <1 cm diameter, all tree conditions combined.

These data imply that Al taken up by the fine root system is not translocated proportionately even a short distance along the root system. Bioassay experiments conducted by the MOE confirmed that most of the Al taken up by sugar maple roots was localized in the epidermal and cortical cell walls and that very little Al made its way into the vascular tissue. Research with spruce arrived at similar conclusions, that Al root concentrations were greatest in the root cap, the meristem, along the outer cortical cell layers, decreased towards the endodermis and were lowest (virtually absent) in the vascular tissue.[3, 54]

9.5.3.1 Aluminum and Sugar Maple Decline

The agricultural community has long known that Al can be toxic to plant roots. Root Al toxicity is a popular theory and has been implicated in forest decline in Europe and the U.S.[79, 110] The chemistry of soil Al in regards to plant availability and toxicity is not well understood. In relatively simple soil aqueous solutions Al may exist as an assortment of forms ranging from monomeric Al^{3+}, $All(OH)^2$, $AlCl_2$, AlF, $AlSO_4$ and hydroxy-Al polymers.[122] These forms vary in their relative abundance and toxicity. Based on extensive soil lysimeter studies in two watersheds in the Muskoka-Haliburton area of Ontario, about 40% of the Al in soil water was in the form of AlF and about 30% each as organic Al and monomeric Al^{3+}.[61] The organic and monomeric forms predominated in the A and B horizons while AlF dominated the lower B and C horizons.

Comparatively few studies have explored the Al root relationship of sugar maple. Research at the University of Toronto, McGill University and the MOE confirmed that fine root Al concentrations of sugar maple seedlings increased with available Al concentrations in the growing medium. Levels of available Al ranging from 1 ppm to 100 ppm resulted in root Al concentrations of less than 1000 ppm to over 9000 ppm respectively.[77] By comparison, available Al in the rooting zone soil from the Muskoka sites averaged 18 ppm but ranged up to 37 ppm. The corresponding fine root Al concentration at these sites ranged from just less than 2000 ppm to 5800 ppm.

Sub-toxic concentrations of Al have been shown to impede the growth of fine feeder roots and reduce fine root branch development.[109] It is also thought to interfere with the ability of the roots to absorb essential soil nutrients.[101] German research with Norway spruce suggests that a Ca/Mg ratio in the roots of less than 1 induces root damage.[70] The Ca/Mg ratio of healthy trees from Muskoka averaged 6.2, whereas declining sugar maple trees had an average Ca/Mg root ratio of 5.5. Although the relative sensitivity of sugar maple to root Al toxicity compared with Norway spruce is not well documented, MOE research found that the Ca/Mg root threshold ratio of 1 would not occur for sugar maple below about 300 ppm available Al in soil. However, effects were observed in sugar maple with root Ca/Mg ratios of between 2 and 3, which corresponded to the range of 40 to 80 ppm available Al in the soil. These effects included a disruption of the root's ability to absorb and transport moisture, a reduction in stomatal conductance and net photosynthesis, and a disruption in nutrient uptake.[77] These symptoms are indicative of trees under physiological stress and occurred in laboratory seedlings exposed to soil Al concentrations similar to and slightly higher than those encountered in sites across Muskoka.

Al strongly interferes with P metabolism. Aluminum may induce the accumulation of large amounts of inorganic P in the roots and reduce P availability for symplastic uptake and subsequent translocation to the foliage.[8, 15] Therefore, the ratio of root P/Al, or the ratio of foliar P to root Al, may be indicators of P/Al antagonism. Using the MOE experimental data for comparison, the study plots can be ranked relative to the degree of P/Al antagonism.

Table 24 summarizes the root P/Al and foliar P/root Al ratios for the 11 study sites. Consistent effects were observed in sugar maple bioassay studies at root P/Al ratios below 0.18.[77] None of the study plots had root P/Al ratios this low. However, the declining trees at all but one of the Muskoka plots had a lower root P/Al ratio than the healthy trees, indicating a greater amount of P/Al antagonism. The Muskoka plots had much lower root P/Al ratios than either the Peterborough or Thunder Bay study sites, reflecting the much higher available Al concentrations of the podzolic soils. Using the root P/Al ratio the study sites can be ranked from most affected to least affected by P/Al antagonism: Cecebe Lake > Horn Lake > Magnetawan > Point Ideal > Musquash River > Etwell > Algonquin Park > Thunder Bay > Indian River > Woodview.

The MOE bioassay found that the foliar P/root Al ratio had a clear gradient relative to observed effects (adverse effects consistently measured at foliar P/root Al ratio between 0.2 and 0.4).[77] Trees from six of the eight Muskoka study plots fell within this range, and declining trees from all but one site in this region had lower ratios, relative to the healthy trees from the same plots. Ranked from most to least affected by P/Al antagonism using the foliar P/root Al ratio the plots are: Cecebe Lake > Horn Lake > Magnetawan = Algonquin Park > Point Ideal > Etwell = Musquash River > Indian River > Woodview > Thunder Bay. Using either ratio Cecebe Lake, Horn Lake and Magnetawan rank as the most affected and the two Peterborough and the Thunder Bay sites as the least affected.

Aluminum toxicity is characterized by root stunting. This may be related to Al in the root meristem binding to the nucleus and therefore reducing cell division.[54] Aluminum also interferes with the deposition of cell wall polysaccharides and links with pectin, so that the cell walls become more rigid.[47] Plant membranes are integral to the function of most plant processes. It has been speculated that Al binds with esteric P in the phospholipids of the lipid bylayer of the plasmalemma and may induce a stage of membrane permeability known as phase separation. This creates a hydrophillic channel in the membrane allowing the leakage of nutrients out of the plasmalemma and passive Al permeation in.[113] It has also been found that Al binds with the enzyme calmodulin, and that it interferes with the calmodulin-stimulated membrane-bound ATPase activity.[96] This enzyme-related process is integral in maintaining the transmembrane potential, but breaks down under increased Al loading resulting in "leaky" plant membranes, which in turn disrupts many plant processes.

Table 24
Phosphorous/Aluminum Ratio of Sugar Maple Tissue
of 10 Study Sites.*

Study Site	Phosphorous/Aluminum Ratio: Foliar P/Root Al, Healthy	Foliar P/Root Al, Declining	Foliar P/Root Al, Mean	Root P/Root Al, Healthy	Root P/Root Al, Declining	Root P/Root Al, Mean
Magnetawan	0.4	0.5	0.45	1.8	1.7	1.75
Horn Lake	0.4	0.3	0.35	1.9	1.0	1.45
Cecebe Lake	0.3	0.2	0.25	1.1	0.7	0.90
Etwell	0.9	0.2	0.55	4.3	1.0	2.65
Musquash R	0.7	0.4	0.55	3.2	0.8	2.00
Point Ideal	0.5	0.5	0.50	1.8	2.1	1.95
Swan Lake	0.5	0.4	0.45	5.8	2.3	4.10
Muskoka Mean	0.5	0.4	0.45	2.8	1.2	2.00
Woodview	1.1	1.3	1.20	5.9	8.1	7.00
Indian R	0.8	1.1	0.95	5.2	6.6	5.90
Peterborough Mean	1.0	1.2	1.10	5.6	7.4	6.50
Thunder Bay	9.2	22.1	15.70	5.9	5.0	5.45

* Root data not available for Utterson

The distribution of Al in mature sugar maple is illustrated in Figure 10. These data are based on sampling conducted on healthy trees at the Swan Lake and Woodview study sites, and therefore are divided into podzol and brunisol soil types. The Al concentration gradient throughout the tree is: soil (total) > fine roots > coarse roots > upper crown foliage > lower crown foliage > xylem (breast height) > twigs. Although the absolute concentrations are different the gradient is the same for the two soil types. These data confirm that although Al is translocated throughout the tree, the greatest concentration gradient occurs at the soil/fine root interface.

Although direct evidence is lacking to link tree decline with Al toxicity, the literature (and research conducted and sponsored by the MOE) suggests that adverse physiological effects have been observed at concentrations only slightly higher than those encountered in the Muskoka study region. In conjunction with the fact that declining trees consistently had significantly higher root Al concentrations and lower P/Al ratios, the possibility cannot be dismissed that Al toxicity is at least exacerbating tree decline in the Muskoka study region.

9.5.6 Dendrochemistry

Dendrochemistry refers to the determination of the chemical concentrations of wood xylem that has been aged by counting the annual growth rings. It has been speculated that tree ring chemistry may catalogue changes in environmental chemistry, particularly trends in soil chemical concentrations. This hypothesis assumes that elements accumulating in a given tree ring reflect the environmental chemistry in the year in which the ring is formed, and that translocation of these elements between rings is not significant.

A study of tree ring chemistry of three tree species in Georgia detected a significant increase in Pb concentrations in rings corresponding in time with the introduction of leaded gasoline.[90] Some movement of Pb between annual rings was detected in hickory and tulip poplar but not in oak. In a different study, no evidence of inter-ring elemental translocation was observed in shortleaf pine that had elevated concentrations of Fe, Al, Cd, Cu, and Zn in years corresponding to the local history of Cu ore smelting.[4] Similarly, elevated metal concentrations, particularly Al, have been detected in annual growth rings of pine in Alberta, and spruce and sugar maple on Camels Hump in Vermont.[62, 93] In both of these latter studies the increase in dendrochemical concentrations was believed to be related to a parallel increase in soil available metal concentration as a result of an increased degree of soil acidification.

Very little dendrochemical data is available for Ontario tree species. Tree rings of white pine from the Dorset area contained two to three times more Al in the most recent 10 years compared to the previous 10 year period (30 to 50 ppm vs. 17 ppm).[86] This study suggested that an increase in Al tree xylem could be related to increasing available Al levels in the soil as a result of accelerated soil acidification by acidic deposition.

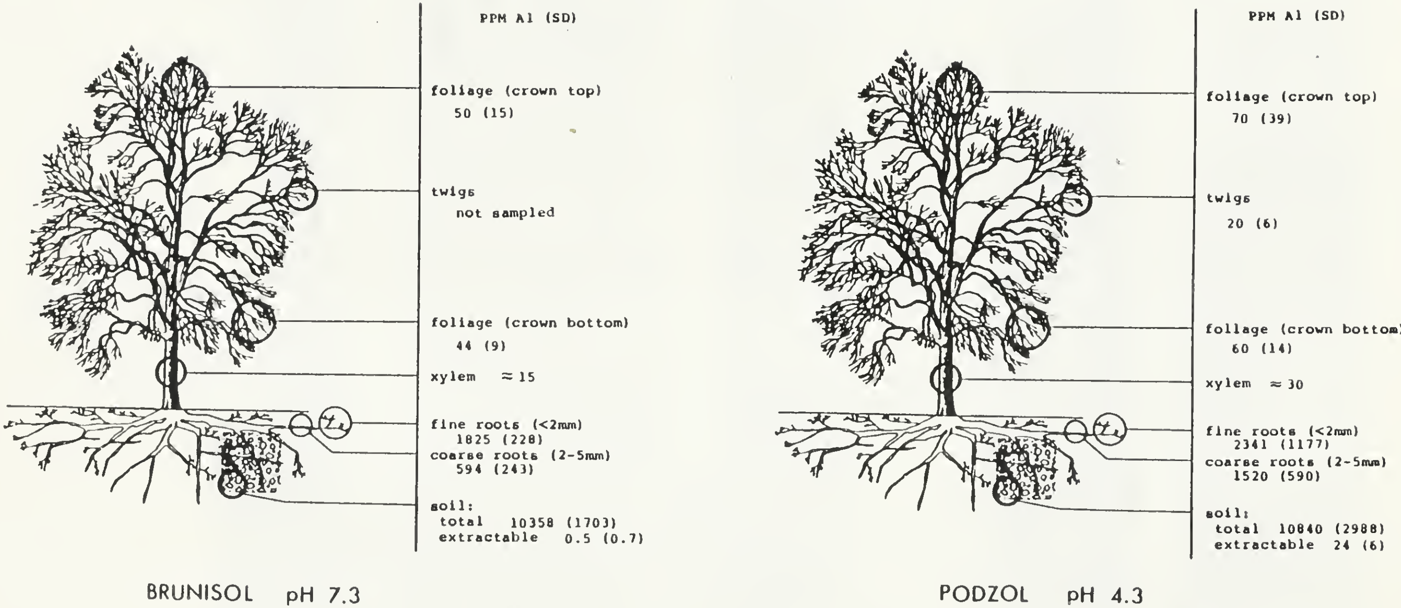


Figure 10
Distribution of Aluminum in Sugar Maple Trees from Two Soil Types.

Dendrochemistry was not originally planned to be part of the sugar maple etiology study. However, limited analysis was conducted on a few maple tree ring series from selected study plots. The Physics Department of Queens University was provided with sugar maple xylem samples from healthy and declining trees from the Etwell and Thunder Bay study sites. Forintek Canada Corp. analyzed xylem samples from the Woodview site. The Queens laboratory did the analyses by PIXE (Proton Induced X-ray Emission spectroscopy), whereas Forintek used EDXA (Energy Dispersive X-ray micro-Analysis emission spectroscopy). The use of PIXE and EDXA for tree ring analysis is experimental. The MOE provided the samples to the two laboratories as part of their methodology development program. Only a few samples were analyzed, no replicate analyses were performed, instrument calibration was not precise (yielding only approximate data) and the resultant data could not be tested statistically. Therefore, the data should be considered for information purposes only.

Differences between study plots were apparent, but concentration trends were not consistent either between trees at the same site or between sites. Generally, metals in tree rings did not illustrate a trend towards increasing concentrations in more recent years. The concentration of Al from sugar maple at the Woodview site remained constant over the last 60 years at less than 10 ppm. At Etwell, where the soil is acidic and Al is freely available, the Al concentration ranged from 17 to 43 ppm with no consistent temporal pattern.

In addition to the analyses conducted by Queens and Forintek, xylem samples of declining and healthy trees from the Horn Lake, Magnetawan and Etwell sites were cut into 10 year increments and supplied to the Forestry Faculty at the University of Toronto for analysis by the more traditional method of INA (Instrumental Neutron Activation). Although more analyses were conducted using an accepted methodology the data should still be considered for information only because of the relatively small sample size and lack of replication. The concentration of Al in tree rings was lower using INA than either PIXE or EDXA.

The INA data are summarized in Table 25. Although the differences were not statistically significant, there was a tendency towards marginally higher concentrations of Al in declining trees. The highest Al concentrations at Etwell and Magnetawan were detected in the most recent 10 years (4.5 and 9 ppm, respectively). Tree ring Al levels at Horn Lake remained constant through time at about 3 ppm.

Figure 11 illustrates the temporal trend of Al in sugar maple xylem derived from the mean INA values. Because of the small sample size and lack of replication the data could not be statistically tested. Non-the-less, the trend suggests that an increase in xylem Al accumulation has occurred in tree rings in the most recent 10 years. This is consistent with the limited literature on this subject and provides circumstantial (although untested) evidence of a recent increase in soil available Al levels.

Table 25
Aluminum Concentration of Sugar Maple Annual Ring Xylem
from Etwell, Horn Lake and Magnetawan.

Time Period	Etwell Healthy	Etwell Declining	Horn Lake Healthy	Horn Lake Declining	Magnetawan Healthy	Magnetawan Declining	Mean All Sites Healthy	Mean All Sites Declining	Mean All Trees
	Aluminum Concentration - ppm								
1975-84	3.0	4.5	3.0	3.0	5.0	9.0	3.7	5.5	4.6
1965-74	3.0	3.0	3.0	2.0	2.0	4.0	2.7	3.0	2.8
1955-64	3.0	3.5	2.0	3.5	2.0	2.0	2.3	3.0	2.7
1945-54	3.0	2.5	4.0	3.0	1.5	6.0	2.8	3.8	3.3
1935-44	3.0	1.5	2.0	2.0	3.0	4.0	2.7	2.5	2.6
1925-34	3.0	2.5	-	-	2.0	6.0	2.5	4.3	3.4
1915-24	2.0	2.0	-	-	-	5.0	2.0	3.5	3.0
1905-14	2.0	2.0	-	-	-	3.0	2.0	2.5	2.3

- data are ppm, single analysis by INA.
- Adapted from Wong (1988)[125]

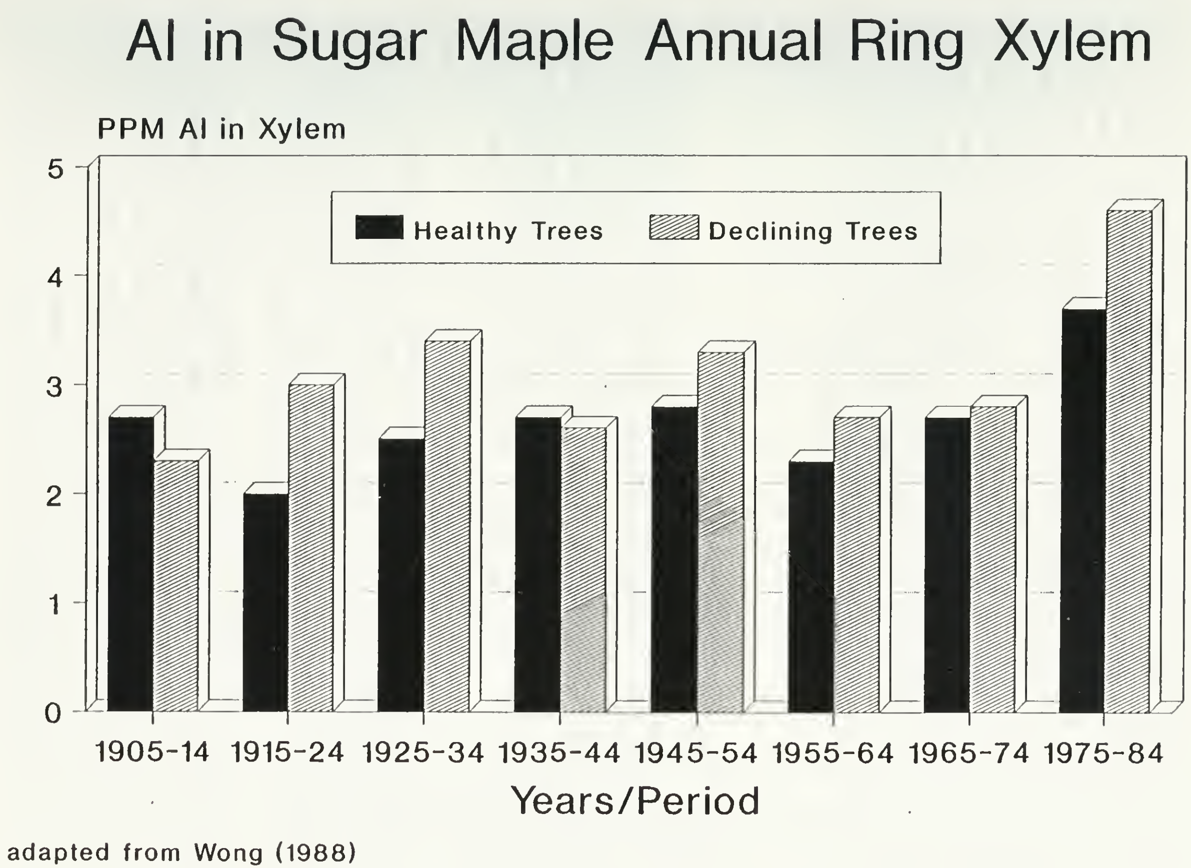


Figure 11
Temporal Distribution of Aluminum in Sugar Maple Xylem.

9.6 Weather

Temperature and precipitation records current to 1988 are available for 45 years for Thunder Bay, 92 years for Muskoka (Huntsville weather station), and 117 years for Peterborough. These data are summarized in Table 26 by winter, spring, summer, fall, growing season and year mean for each of the study regions. Peterborough, being the most southerly, has the highest mean growing season temperature (15.3° C) and the mildest winters (-5.2° C). Growing season precipitation is quite similar, ranging from a low of 403 mm in Peterborough to a high of 460 mm in Muskoka, although the Muskoka region receives considerably more snowfall (331 mm total winter precipitation). As expected, Thunder Bay has the coldest winter (-10.3° C), but it also receives the lowest amount of snowfall (167 mm). The seasonal mean data in Table 26 were compiled from the monthly averages as follows: winter included November, December January and February; spring included April and May; the summer data were compiled from the June, July and August monthly mean; fall included September and October; and the growing season data were derived from the months of May through September. March was excluded because it was the month of greatest variability across the study area, alternating between very winter-like and very spring-like.

9.6.1 Climate Stress and Tree Decline

Traditionally, drought has been considered as the major climate factor affecting tree growth and health. An extensive study of declining roadside sugar maple in the NE USA in the mid-1960s concluded that drought was the primary cause of tree decline.[120] Decline symptomatology can be induced by withholding water. Experiments with both potted and field trees have reversed decline symptoms with irrigation.[5] However, an over-abundance of rainfall also can adversely affect tree growth by reducing the amount of direct sunlight as a result of extended cloudy periods. Less sunlight results in a lower level of photosynthetic activity that in turn lowers the amount of energy produced by the tree.

In contrast, heavy snowfall in the winter is beneficial because it provides increased insulation for tree roots, particularly on shallow soils where the roots are close to the surface. Abundant snow also ensures adequate soil moisture in the early spring. Very cold winter temperatures, in conjunction with low snowfall, can cause extensive root mortality, which is often followed by tree decline the following growing season. Low winter temperatures in combination with low snowfall were cited as a major inciting factor of a maple decline episode in central Ontario in 1964.[29]

Although droughts have occurred, precipitation is infrequently limiting to tree growth in Ontario. Temperature may have a greater impact on tree health than precipitation, particularly for species that are at the edge of their geographic range, as sugar maple is in the northern portion of the hardwood forest zone in Ontario. During prolonged or excessively warm weather, trees attempt to reduce moisture loss through evapotranspiration by closing leaf stomates. Although this is a very successful way to maintain moisture levels within the foliar biomass, by restricting gas exchange through the stomates the photosynthetic rate is also dramatically reduced, thereby inhibiting energy assimilation. With less energy being produced, the tree must draw upon it's stored energy reserves in order to carry on the regular physiological activities that are usually fuelled by energy provided

Table 26
Meteorological Summary of the Three Study Regions.

Season	Peterborough		Muskoka		Thunder Bay	
	Mean Temperature °C (SD)					
Winter	-5.2	(1.5)	-6.4	(1.5)	-10.3	(1.5)
Spring	9.2	(1.6)	7.8	(1.4)	5.7	(1.3)
Summer	18.9	(1.2)	17.7	(2.1)	15.9	(1.3)
Fall	11.6	(1.4)	10.7	(1.8)	8.6	(1.2)
GS	15.3	(1.1)	13.9	(0.9)	11.8	(0.7)
Year	6.2	(0.8)	5.2	(0.9)	2.4	(0.8)

Season	Peterborough		Muskoka		Thunder Bay	
	Mean Total Precipitation mm (SD)					
Winter	225	(54)	331	(75)	167	(63)
Spring	128	(46)	131	(44)	119	(51)
Summer	209	(55)	239	(67)	248	(75)
Fall	136	(51)	179	(53)	144	(70)
GS	403	(81)	460	(109)	451	(93)

GS - growing season.
SD - standard deviation.
Length of weather record:
Peterborough (1867 - 1988)
Muskoka (1911 - 1988)
Thunder Bay (1942 - 1988)

by on-going photosynthesis.

Studies by the MNR have found that incremental growth of some conifers is often correlated with the current spring and previous fall temperatures. Preliminary MOE studies of regional sugar maple growth have detected a similar trend towards extreme early and late growing season temperatures and reduced growth. Unfavourable fall temperatures inhibit bud set and energy assimilation as the tree prepares for dormancy and stores the energy reserves necessary for early growth the following year. Unfavourable spring temperatures interfere with the formation and distribution of growth hormones required to initiate shoot and root elongation and can injure newly emerged tissue.

An inherent degree of climatic variability is common in the temperate zone; therefore, forest trees such as sugar maple are tolerant of a normal level of thermal and precipitation stress. However, climate stress events that are severe in degree or duration, or occur sequentially or concurrently (i.e., spring drought followed by summer drought concurrent with unusually high or low temperatures, or severe events in sequential years) may act synergistically to impose a much more significant physiological stress on the forest.

9.6.2 Climate Stress Frequency in the Study Regions

The climate data were reviewed for the three study regions to determine if adverse climate had contributed to the decline observed in the study plots. It was assumed that temperature extremes could be as stressful as droughts. It was also assumed that thermal and precipitation stress events would be more harmful if they occurred for the entire season. Finally, climate stress was assumed to be greatest when seasonal extremes occurred concurrently.

The mean monthly temperature and precipitation data were obtained from Environment Canada and the mean winter, spring, summer, fall and growing season values were calculated. These were the basis of the climate summary provided in Table 26. The mean seasonal data for each study region were plotted and the graphs photocopied onto clear acetate. Years in which adverse climate occurred in concurrent seasons could be readily identified by simply overlaying the various graphs. The seasonal combinations considered to represent a climate stress event were; low winter precipitation concurrent with low winter temperature (potential for root damage on shallow soils), low winter precipitation concurrent with low spring precipitation (acute early season drought), low spring precipitation concurrent with low summer precipitation (prolonged drought), low spring precipitation concurrent with high spring temperature (acute water balance/loss stress), low summer precipitation concurrent with high summer temperature (prolonged water balance/loss stress), low growing season precipitation concurrent with high growing season temperature (extreme water balance/loss stress), and years in which the growing season was either extremely warm or cold. The selection of a year as a stress year was done on a relative rather than quantitative basis. Only the most extreme four or five years were selected for each season for each study region. This was done because the weather records were of different lengths for the three study areas and because a certain level of climatic variation is normal (a specific cut-off point, for example >1 standard deviation from the mean, is

arbitrary and may not indicate an unusally extreme event). Choosing only the most extreme years ensures that only truly unusual events are considered. The climate stress years identified in this manner are listed in Table 27.

Years in which more than one of these climate stress events occurred would be particularly stressful for the trees. If the frequency of the climate stress events were low, their cumulative effect would be minimized, as healthy trees generally have the flexibility to recover from periodic stress. However, the recovery flexibility in the between-stress period can be significantly eroded if tree vigour is reduced as a result of additional biotic or abiotic stresses, such as poor woodlot management, disease, or insect epidemics. If the frequency of climatic stress events was high, their cumulative effect would be maximized, as the trees are denied the necessary between-stress recovery period. The worst-case scenario would be a period of high climate stress frequency concurrent with severe additional (non-climatic) stresses.

In the 45-year weather record for Thunder Bay there were nine climate stress years. Three of these were multiple stress years, for a total of 14 significant climate stress events. This works out to a probability of a climate stress occurring about one in every three years in Thunder Bay. The climate stress years were; 1950, 1953, 1955 (2X), 1978, 1980, 1981 (2X), 1983, 1987, and 1988 (4X). It is apparent that the frequency of climate stress has been much higher in the 1980s than in any other time in the relatively short weather history. The 1980s were particularly critical in regards to climate extremes. As elsewhere in the province, the 1988 growing season was both very dry and very warm, although 1987 actually recorded the highest mean annual temperature. The highest fall temperature and the second highest summer temperature occurred in 1983. Winter temperature has fluctuated dramatically. The warmest winter occurred in 1983, which was preceded in 1982 by the second coldest winter. The record low mean winter snowfall occurred in 1981. This was concurrent with the lowest spring, summer, and growing season precipitation. The coldest winter, 1978, was concurrent with the second lowest snowfall.

In the 92-year weather record for Muskoka there were 14 climate stress years. Two of these were multiple stress years, for a total of 18 significant climate stress events. On average, this works out to a probability of a climate stress event occurring about one in every five years in Muskoka. The climate stress years were; 1921, 1924, 1926, 1927, 1929, 1935 (2X), 1944, 1955, 1976, 1977, 1978, 1986, 1987 (4X), and 1988. There were two periods of high climate stress frequency; the 1920s, and mid 1970 through to the present. The 1920s were characterized primarily by consistently low seasonal temperatures and isolated seasonal droughts. The latter period of climate stress was more severe because the frequency was higher, it was longer, and it combined both thermal and precipitation events. High temperatures and low precipitation characterized the 1988 growing season. The 1987 spring temperature was near maximum, concurrent with the second highest growing season temperature and fifth lowest growing season precipitation. High spring temperature and low spring rainfall also occurred in 1986. The winter of 1985 was the coldest of the 92-year weather record. The second coldest winter occurred in 1978, which was also a year of well below normal snowfall. The four year period 1975 to through 1978 was characterized by spring drought. Four sequential years of low spring precipitation is unique in the Muskoka weather record. Although all the Muskoka study plots would have been affected, these spring droughts in combination with the cold/low snowfall winter of 1978 would have been particularly damaging to the study plots characterized by thin soil. This would include Magnetawan, Cecebe Lake, Etwell and Musquash River.

Table 27
Climate Stress Years of the Three Study Regions.

Climate Combination	Thunder Bay	Peterborough	Muskoka
low winter precip. & low winter temp.	1978	1957, 1977	1935, 1978
low winter precip. & low spring precip.	1981	1906, 1941, 1977, 1987	1935
low spring precip. & low summer precip.	1953, 1981, 1988	1971, 1987	1929, 1944, 1976
low spring precip. & high spring temp.	1980, 1987	1941, 1955	1977, 1986, 1987
low summer precip. & high summer temp.	1988	1955, 1986, 1987, 1988	1987, 1988
low grow season precip. & high grow season temp.	1955, 1988		1987
extreme low/high grow season temp.	1950, 1955, 1983, 1988	1869, 1926, 1972, 1973, 1976, 1979, 1982	1921, 1924, 1926, 1927, 1955, 1987
Multiple Stress Years	1955, 1981, 1988	1941, 1955, 1977, 1988	1935, 1987

Chronologically Listed Climate Stress Years:

Thunder Bay - 1950, 1953, 1955 (2X), 1978, 1980, 1981 (2X), 1983, 1987, 1988 (4X).

Peterborough - 1869, 1906, 1926, 1941 (2X), 1955 (2X), 1957, 1971, 1972, 1973, 1976, 1977 (2X), 1979, 1982, 1986, 1987 (3X), 1988.

Muskoka: 1921, 1924, 1926, 1927, 1929, 1935 (2X), 1944, 1955, 1976, 1977, 1978, 1986, 1987 (4X), 1988.

In the 117-year weather record for Peterborough there were 15 climate stress years. Four of these were multiple stress years, for a total of 20 climate stress events. On average, this works out to the probability of a climate stress event occurring about one in every six years in Peterborough. The climate stress years were; 1906, 1926, 1941 (2X), 1955 (2X), 1957, 1971, 1972, 1973, 1976, 1977 (2X), 1979, 1982, 1986, 1987 (3X), and 1988. It is apparent that, similar to both Thunder Bay and Muskoka, the frequency of climate stress in Peterborough has been much higher in the most recent two decades. As elsewhere in Ontario, both 1988 and 1987 were unusually warm and dry. The coldest growing season occurred in 1972. This was followed in 1973 by the warmest growing season on record. The 12 year period from 1973 through 1984 was characterized by well above average growing season temperature. Six of these 12 years were clustered just below the 1973 record high. Within this period, the winter of 1977 was the fifth coldest, which was concurrent with the lowest snowfall in the 117-year weather history. The record low snowfall of 1977 was followed by spring precipitation that was well below normal. Woodview, because of it's very shallow soil, would be the most affected of the two Peterborough study plots.

Table 28 summarizes the climate stress events for the three study areas in relation to five 20-year periods from 1891 (the most recent period, 1971 to 1988, has only 18 years). These data are illustrated in Figure 12 and clearly show that the frequency of climatic stress events has been higher in the last two decades than at any other time this century for the Peterborough and Muskoka regions and since 1942 (the length of the weather record) for Thunder Bay. The probability of the occurrence of a climate stress event was 1 in 2 years or less for each of the three study regions from 1971 to 1988. This high frequency of climate stress has a significant adverse effect on tree vigour because of the cumulative nature of stresses when they occur so close together.

Decline symptomatology usually takes a few years to become apparent subsequent to the inciting stress. The woodlot owners reported that decline symptoms were first observed in the early 1980s at the study plots. This is consistent with the latent reaction to climate stress in the mid to late 1970s. Continued climate stress through the 1980s may further inhibit tree recovery or could contribute to a subsequent decline episode. The climate stress that occurred in the last 10 to 15 years in all three study areas was severe enough and frequent enough to be considered as an inciting factor of the maple decline observed in the mid to late 1980s.

Table 28
Frequency of Climate Stress Events in the Three Study Regions.

Study Area	Frequency (Probability)				
	1891-1910	1911-1930	1931-1950	1951-1970	1971-1988
Thunder Bay	ND	ND	1 (1:20)	3 (1:7)	10 (1:2)
Muskoka	ND	5 (1:4)	3 (1:7)	1 (1:20)	9 (1:2)
Peterborough	1 (1:20)	1 (1:20)	2 (1:10)	3 (1:7)	13 (1:1)

- climate Stress defined in text.
- probability eg. 1:20 = likelihood of occurrence is 1 year in 20 years.

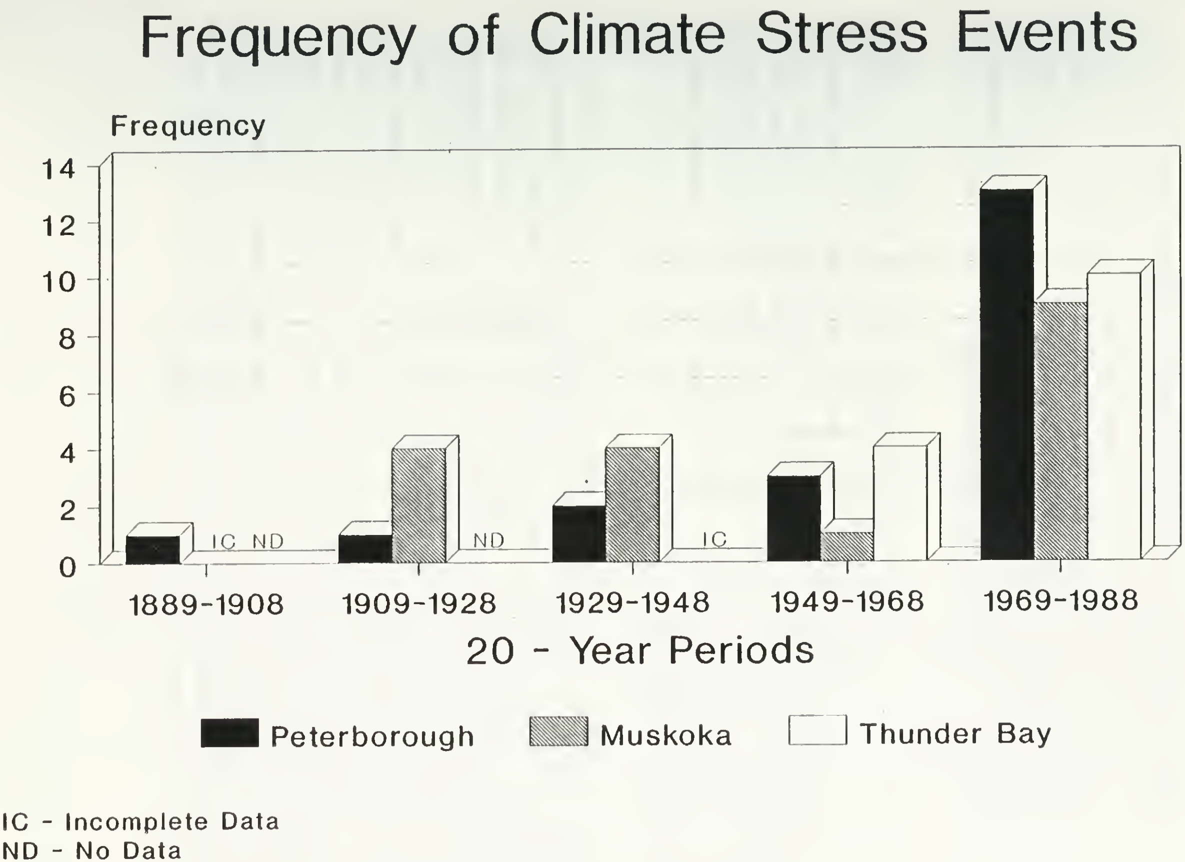


Figure 12
Frequency of Climate Stress Events in 20-Year Periods for the Three Study Areas.

9.6.3 Forest Decline and Climate Change

The climate variability encountered in the last two decades is not unique to Ontario. A recent review of climate across the continental USA revealed that winters in the period 1975 to 1983 were either much warmer or much colder than normal.[57] Computer climate modelling concluded that six abnormal winters in an eight year period is a very rare event, occurring only once every 1100 to 1250 years. It was suggested that a series of extreme years preceded by a 60 year period of normal variability is either an unusually rare event in a reasonably stationary climate, or it represents a shift towards a climate change. Figure 13 illustrates the trend line of the mean annual temperature for the three Ontario study regions. These lines suggest that the mean annual temperature has increased during this century by about 1.5° C in Peterborough, slightly more than 0.5° in the Muskoka area and slightly less than 0.5° in Thunder Bay.

Global warming associated with the increase in greenhouse gases has emerged as a major political and scientific issue. The level of atmospheric CO_2 has increased about 25% since 1850 as a result of fossil fuel combustion and deforestation. The levels of trace greenhouse gases such as chlorofluorocarbons and methane have increased by considerably larger proportions.[94] However, there is considerable uncertainty regarding the effects that an increase in atmospheric greenhouse gases will have on global climate. An increase of only a degree or two in the average global temperature, which is a conservative prediction, would mean an increase of between 4° and 6° in the temperate zone, where most of Canada's forests are situated.[91] Such a dramatic increase in temperature would certainly affect precipitation patterns, but models are more shaky in this regards, predicting both increases and decreases in regional summer rainfall.

The Goddard Institute for Space Studies has confirmed that 1987 and 1988 were the warmest years in the 100-year record of instrumentally recorded global temperatures.[58] High temperatures in the next few years would continue the current robust warming trend evident in the 1980s and would be difficult evidence to ignore regarding the validity of climate change. If the climate models are correct, the world will not only be warmer than it has been in tens or perhaps hundreds of thousands of years, but the change will occur more rapidly than ever before. Each rise of 1° in the global temperature means a northward shift in the range of the tolerant hardwood forest tree species of about 100 to 150 km. Using the current climate change scenarios generated by both the more conservative and the radical models, the range of species such as sugar maple, beech, and yellow birch will shift northwards by as much as 500 to 1000 km within the next century, and possibly sooner.[91] Fossil records reveal that these species have migrated in the past in response to changing climate during periods of glaciation, but this migration is usually accomplished at a rate of about 20 or so km a century (some coniferous species appear to be able to move much faster, perhaps as much as 200 km a century). In order to respond to the shift in their range associated with the predicted climate change the tolerant hardwood forest species would have to migrate 40 or 50 times faster than they have been able to in the past, unquestionably an unlikely probability.

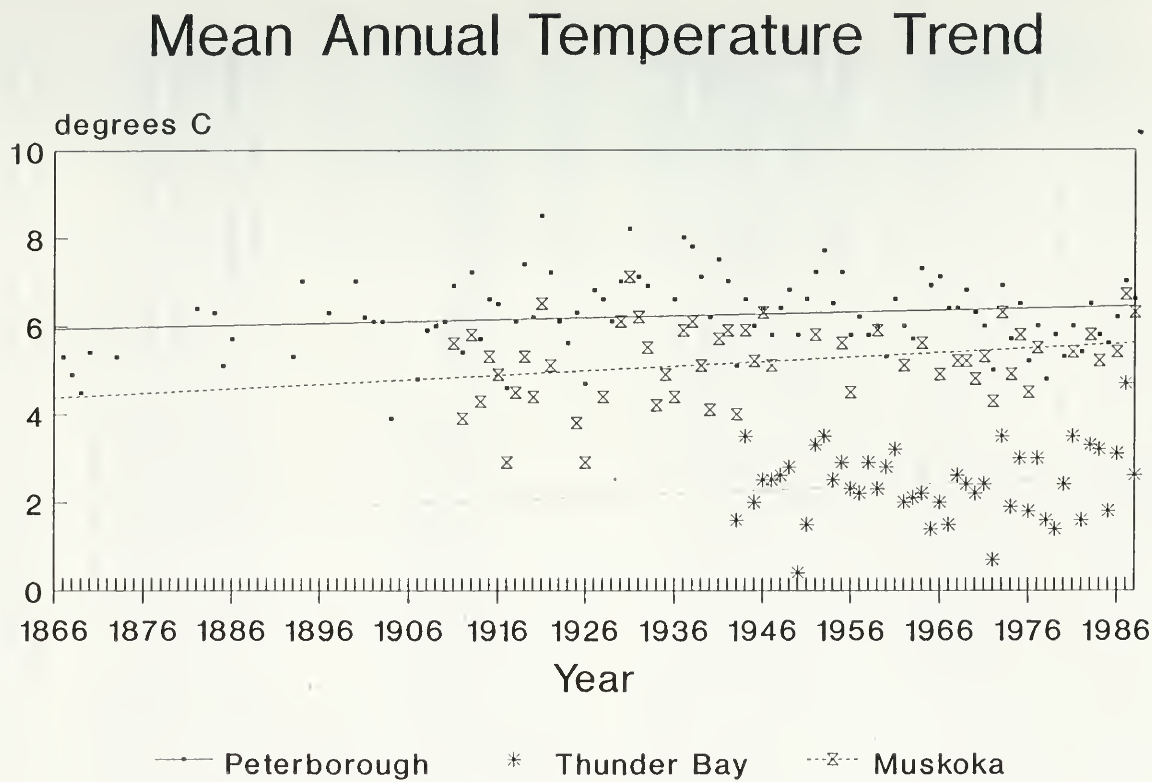


Figure 13
Mean Annual Temperature Trend Line for the Three Study Areas.

Decline and mortality would occur first along the southern edge of the range as the climate quickly becomes inhospitable. Trees in the central portion of the range would not be affected for several decades. The rate of migration into the northern fringes of the new range is not just a function of when the climate becomes favourable but is also dependent on the complex relationships with other species occupying the site, and various soil types, and nutrient regimes. But the biggest question relates to the ability of the species being able to adapt in a very short time to radically different growing conditions across the new range, such as temperature and precipitation variation, changes in day length, and the intensity of solar irradiation. The population of any tree species is composed of distinct ecotypes and subspecies that have adapted over a long period of time to specific local or regional conditions. Evolutionary adaptation requires time. If this specialization is genetically "hardwired" then some species may not have the genetic elasticity to adapt to climate change in the abbreviated time frame in which it will occur.

Although the magnitude and timing of climate change is still contested there is general agreement that the driving force behind increasing levels of greenhouse gases is atmospheric pollution, particularly the combustion of fossil fuels. However, the connection between forest decline and pollution is obscured. The trees decline and eventually die of secondary infection as a result of reduced vigour, caused in part by unfavourable climatic events, which were triggered by higher levels of atmospheric greenhouse gases, which in turn are directly related to air pollution. As the pollution connection is three or four times removed from the resultant problems in the forest, the cause and effect relationship remains elusive.

9.7 Pathology and Entomology

From 1984 to 1989 observations were made to document the presence of disease and insects at each of the 11 study plots. Samples were collected for examination in the Phytotoxicology laboratory when organisms could not be identified in the field.

9.7.1 Pathology Summary

In Table 11 it was shown that (in 1987) 9.8% of the trees in the study plots had either stem cankers or fruiting bodies. Table 12 indicated that these trees had a significantly higher Decline Index. Table 29 summarizes the common disease organisms observed at the plots from 1984 to 1989. These diseases are endemic, and their presence can have a considerable impact on the vigour of individual trees. However, most of the observed fungi are secondary and tend to invade the tree only after it has been previously stressed or wounded. They further weaken the tree and in this way are considered to be contributing factors in the decline observed on the study plots.

A possible exception is *Armillaria mellea*, or shoe string root rot (also known as honey fungus). This root rot pathogen was isolated more frequently and the degree of infection was greater on roots from declining trees. The characteristic black flattened rhizomorphs were more frequently observed on stumps and under the bark at the base of the stem of severely declining trees at one of

Table 29
Summary of Disease Organisms Observed at
the Study Sites.

Disease Organism	Frequency of Observation
Armillaria mellea (shoe string root rot)	regularly observed
Coriolus versicolor (trunk/wood rot)	infrequently observed
Eutypella parasitica (stem canker)	occasionally observed
Fomes fomentarius (trunk/wood rot)	occasionally observed
Ganonderma applanatum (trunk/wood rot)	occasionally observed
Nectria galligena (stem/target canker)	occasionally observed
Oxyporus populinus (trunk/wood rot)	infrequently observed
Pleurotus ulmarius (trunk/wood rot)	infrequently observed
Polyporous cuticularis (stem conk/canker)	infrequently observed

- from observations and laboratory examination of samples collected between 1984 and 1989.

the two Peterborough sites (Woodview) and four of the Muskoka study plots (Magnetawan, Etwell, Cecebe Lake and Musquash River). These five plots consistently had the highest mean plot Decline Indices and the greatest frequency of severely declining trees. This strongly suggests that *A. mellea* is an aggressive and well established pathogen in these plots. It is likely that *A. mellea* is the most significant pathogen and is directly contributing to tree mortality.

Nematodes have been associated with declining maple in the NE U.S.A. Researchers in Massachusetts concluded that the root nematode, *Xiphinerma americanum*, may have been the primary causal agent of a sugar maple decline episode in that state in the late 1960s.[17] In the summer of 1987 the MOE awarded a research contract to Ridgetown College to investigate the relationship between nematodes, and MLOs (Mycoplasma-Like-Organisms), and declining trees at the 11 study sites. Results from this study concluded that MLOs were not associated with tree decline. Plant parasitic nematodes were encountered in soil from the study plots but not in sufficient numbers to have contributed significantly to tree decline.

Many maple syrup producers complained of slow tap hole closure and wood staining and/or secondary fungal infection around the tap wound. Slow tap hole closure is a function of slow cambial growth and/or infection by a pathogen that kills the wood near the tap wound. Trees which are stressed are more likely to experience slow tap hole closure because cambial growth would be reduced and poor tree vigour would lower the tree's resistance to secondary infection. Sugar maple with normal vigour is classed as low in it's resistance to wood decay fungi.[9] A tap hole makes a fresh wound in the sapwood, bypassing the protective function provided by the bark. The environment inside the tap hole is ideal for infection because it is protected, moist, and maple sap is relatively high in sugars and related carbohydrates. Fresh sapwood stains naturally. Sapwood, when exposed to the air, oxidizes rapidly, resulting in the conversion of cell cytoplasmic contents to dark coloured phenolic compounds.[50] These phenolic compounds are very effective fungicides and are formed to prevent the spread of decay fungi beyond the immediate area of the wound. A healthy tree forms this phenolic fungicide barrier quickly and is able to "wall off" the wound area to prevent disease spread. Trees under stress, or those with inherently low vigour, form this protective phenolic layer more slowly and the phenolic compounds are less effective in controlling disease infection and rate of spread within the wood. Suggestions to reduce tap hole infection and promote wound healing are provided in Section 11.7.

9.7.2 Entomology Summary

In Table 11 it was shown that 27.3% of the trees on the study plots had scars from the sugar maple borer or, in 1987, were defoliated to some degree. Wood boring and defoliating insects are by far the most significant in regards to their contribution to tree decline.

Table 30 summarizes the common insects encountered at the study plots from 1984 to 1989. The leaf blotch miner and spindle gall mite are endemic and, generally, have a negligible impact on tree health. The pitted ambrosia beetle was very common at all sites. This insect tunnels into the pith of maple seedlings at about ground level, causing the foliage to turn brown early in the summer. The bruce spanworm and saddled prominent were most active at Swan Lake, but were occasionally observed at Point Ideal. In 1989 severe gypsy moth defoliation occurred in isolated sugar maple stands immediately southeast of the Peterborough study plots.

The sugar maple borer may severely affect individual trees but it rarely has a significant impact on the stand. Sugar maple borer was most active in the Magnetawan and Etwell plots. These insects eat the new wood just under the bark along the trunk. If their feeding tunnels girdle the stem the tree will die above the point of feeding. However, the wood of trees that are not killed outright, is weakened in the area of feeding and in a wind storm the tree often breaks off at the borer wound. Maple borer wounds, like any open wound, are important infection courts for secondary disease organisms.

Defoliating insects have the potential to be very damaging to sugar maple stands. The most common sugar maple defoliator is the forest tent caterpillar. All of the study plots have either historically or recently experienced severe defoliation.

Since 1868, there has been an outbreak of this insect somewhere in Ontario on average about every 10 years. In a specific area the tent caterpillar reoccurs with an 11 to 15 year cycle. The largest outbreak was in 1948-1956, when most of the province was infested and severe defoliation was widespread.[97] In the Muskoka region, there have been epidemic outbreaks resulting in severe defoliation in 1935-1939, 1948-1956, 1960-1965, 1973-1978 and 1987-1989. There has been chronic forest tent caterpillar defoliation near the Thunder Bay plot for the last 14 years; however, feeding activity has centred on aspen and defoliation of maple, although severe, is usually scattered. Forest tent caterpillar defoliation in the vicinity of the Peterborough study plots is less well defined. Although the plots were likely defoliated during the province-wide epidemic in the late 1940s and early 1950s, there is no record of subsequent severe outbreaks in this region. Moderate defoliation was reported at the Woodview plot in 1979 and 1980. However, this outbreak must have been very localized because defoliation was not observed at the Indian River site only a few km to the east.

Table 30

Summary of Insect Activity Observed at the 11 Study Plots.

Insect	Frequency of Observation
Cameraria aceriella (leaf blotch miner)	endemic
Corythylus punctatissimus (pitted ambrosia beetle)	regularly observed
Epinotia aceriella (trumpet skeletonizer)	infrequently observed
Glycobius speciosus (sugar maple borer)	occasionally observed
Heterocampa guttivitta (saddled prominent)	infrequently observed
Malacosoma disstria (forest tent caterpillar)	regularly observed
Operophtera brucata (bruce spanworm)	infrequently observed
Vasetes aceris-crumena (spindle gall mite)	endemic

- from observations between 1984 and 1989.

The following is a catalog of defoliation (mostly by tent caterpillar) in the Muskoka area.

1935-1939:	- general defoliation across central Ontario, severe and repeated (i.e., twice in the same growing season) in some areas.[97]
1948-1956:	- general defoliation across central Ontario in conjunction with province-wide outbreak, severe and repeated in some areas.[97]
1960-1965:	- general defoliation across Muskoka, Haliburton and Algonquin Park, severe and prolonged in some areas.[97] - forests in the eastern Muskoka area are 50% - 85% defoliated by bruce spanworm.[30]
1966-1972:	- no record of significant defoliation.
1973:	- tent caterpillar population building, moderate but no severe defoliation reported.[31]
1974:	- tent caterpillar population increased dramatically, isolated pockets of severe defoliation, egg mass counts predict outbreak to epidemic proportions in 1975.[32]
1975:	- moderate to severe defoliation across 2,000,000 ha (20,000 km^2) of central Ontario. - some areas around Georgian Bay, Muskoka and Algonquin Park defoliated twice, second time after July refoliation.[33].
1977:	- area of moderate to severe defoliation expands to 3,380,000 ha (33,800 km^2).[35]
1978:	- total area of defoliation drops to 15,000 ha, severe defoliation still encountered in the Parry Sound area (8,000 ha) where sugar maple mortality exceeds 80% in some woodlots. - up to 50% of the sugar maple is completely defoliated in areas around Owen Sound, where maple mortality overall averages 30%.[36]
1979-1985:	- tent caterpillar population collapses, no reports of significant defoliation in the Muskoka area.
1986-1987:	- forest tent caterpillar population surges to epidemic proportions by spring 1987, but areas of severe defoliation still scattered.
1988:	- moderate to severe defoliation across 3,965,229 ha, very similar in extent to the 1975-1978 epidemic. - egg mass counts predict record defoliation for next year.[38]
1989:	- although the insect is still present across a large area, the predicted severe defoliation did not materialize, perhaps because of weather-related egg/insect mortality.
1990:	- defoliation was very scattered and isolated, defoliation not a problem regionally.

Severe and extensive maple decline was reported over 28,500 ha in the Muskoka region from 1978 to 1980.. Over half of the maple stands surveyed by the Forest Insect and Disease Survey crews had more than 25% mortality. The volume of timber lost as a result of this decline episode was estimated at 2 million m^3 and valued at $19.5 million.[37] This decline occurred immediately after one of the most extensive, severe forest tent caterpillar epidemics recorded. Based on interviews with the woodlot owners, all of the Muskoka area study plots were moderately-to-severely defoliated during this epidemic. The Magnetawan and Etwell sites were the most severely affected because both were defoliated for three consecutive years and both were defoliated twice in one year during the three year epidemic. The Horn Lake, Cecebe Lake, Utterson and Musquash River sites were all severely defoliated for three consecutive years. Point Ideal was somewhat less affected, having been severely defoliated for only two consecutive years. The defoliation status of the Swan Lake site is less certain, although it is believed to have been only moderately defoliated.

The study plots were examined annually by MOE scientists during the most recent outbreak of forest tent caterpillar. In 1987 Swan Lake, Etwell, Horn Lake and Point Ideal received only light defoliation. Moderate defoliation was observed at the Magnetawan, Cecebe Lake and Musquash River study sites. The foliage was completely stripped from trees at the Utterson plot. The degree of defoliation was generally more severe in 1988 at all sites except Point Ideal, which had been sprayed with the biological insecticide BT. All trees at Etwell, Magnetawan, Musquash River and Cecebe Lake were completely defoliated. The severity of defoliation was much less in 1989. Etwell, Musquash River and Magnetawan were moderately defoliated, whereas the other plots were only light-to-moderately defoliated. Defoliation was negligible at Point Ideal.

In light of the severity of defoliation that occurred at the study plots in the Muskoka region there can be little doubt that the forest tent caterpillar epidemic of the mid to late 1970s was a significant stress on the trees and that defoliation contributed to the decline at most sites. The stress associated with defoliation would have been acutely exacerbated by the consecutive spring droughts that occurred from 1975 through 1978. The study plots that were defoliated most often and most severely (Magnetawan, Cecebe Lake, Etwell and Musquash River) are also the sites with the most severe tree decline.

Figure 14 illustrates the extent of defoliation by forest tent caterpillar in 1977 and 1988, and the area that was defoliated in both epidemics. It is apparent that Muskoka is a high risk area for defoliation stress, and in conjunction with the high frequency of climate stress in the last two decades, the tolerant hardwood forest in this region continues to endure a chronically high level of environmental stress.

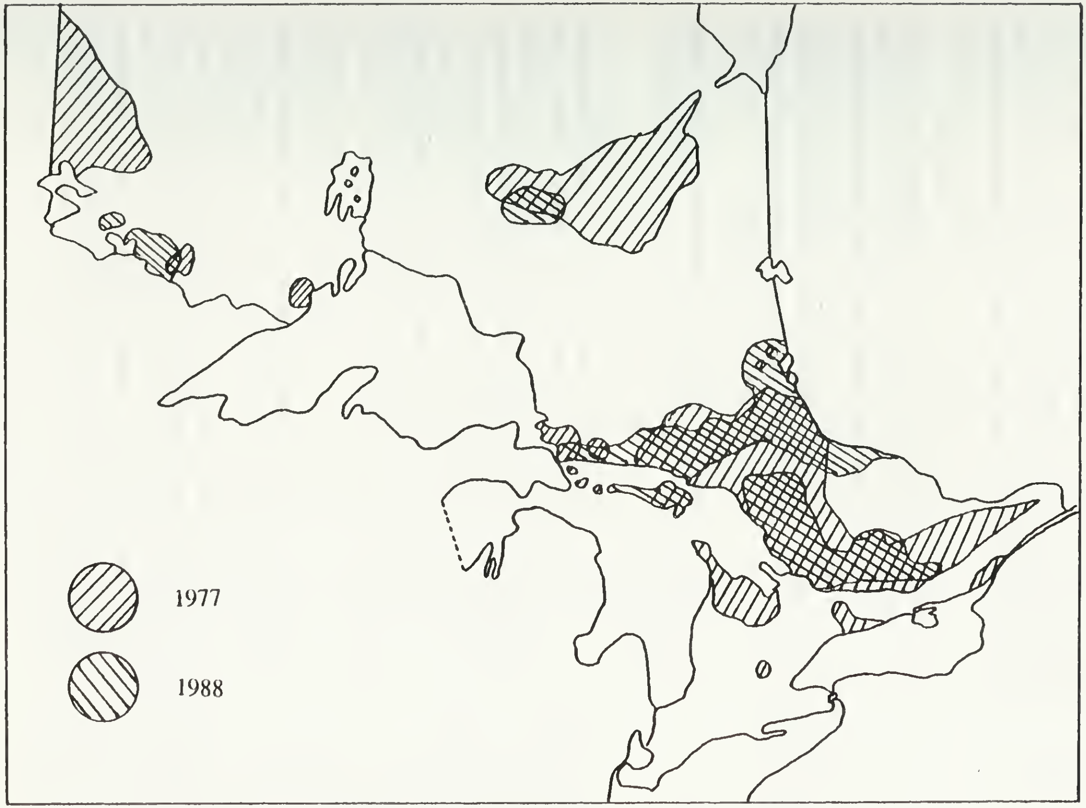


Figure 14
Extent of Severe Defoliation by Forest Tent Caterpillar in 1977 and 1988.

9.8 Root Starch Reserves

Trees produce energy through photosynthesis, and green leaves are the tree's photosynthetic factories. Given favourable growing conditions, trees produce roots and xylem during times of the year when leaves are absent. Therefore, during seasons when leaves are present, trees must produce more energy than what is immediately required in order to provide a source of stored energy reserves to fuel metabolic processes that occur during non-foliar time periods. Trees store photosynthetically-derived energy in the form of starch. In sugar maple, starch is stored in ray parenchyma cells and in living xylem fibres. Starch may be stored in almost any location in the tree where wood xylem is produced, however, thick roots near the base of the tree appear to be the favoured storage organ.

Root starch reserves vary considerably during the year. Starch accumulates during the growing season and is highest in the late summer and early fall, having assimilated and stored photosynthate from foliar activity all summer.[118] Root starch reserves are slowly depleted through the fall, winter and early spring, as the tree uses energy to fuel root growth, seed production, general maintenance, and metabolic functions. Bud flush and early foliar and shoot elongation in the spring utilize large quantities of stored starch, therefore reserves are lowest at this time of the year. As the foliage becomes functional the tree begins the steady build-up of starch deposits.

The quantity of starch in root tissue can, therefore, be used as a monitor of the vigour of the tree and it's ability to withstand environmental stress. Vigorous trees in a good state of physiological preparedness will have root starch concentrations in the fall of between 12% and 15%.

Disks of wood xylem 2 cm in diameter were collected from the buttress roots of trees with a gradient of decline symptoms from each of the study plots in the early fall of 1986. The samples were placed in labelled plastic bags and packed in ice immediately after collection in the field and stored frozen until preparation for analysis. Starch concentrations were determined colorimetrically and expressed as percent starch per gram of dry weight of ETOH extracted root tissue.[117] Root starch reserves of declining trees ranged from less than 3% to 14% and averaged about 9%. There was a marked tendency towards very low starch reserves in severely declining trees. By comparison, the root starch concentration of healthy trees averaged about 12% and ranged from 9% to 18%. The lowest root starch levels were consistently detected at the Magnetawan and Etwell plots.

Mortality is common in trees with root starch reserves less than 3%. Trees with root starch reserves between 3% and 5% may not decline further, but the resurgence of an environmental stress is often terminal. Trees with greater than 5% root starch in the fall usually recover.[116] Most of the declining trees sampled had root starch levels greater than 5%. Therefore, many of the symptomatic trees had the energy reserves necessary for recovery when they were sampled in 1986. In fact, recovery was evident (improvement in general tree condition) at 6 of the 11 study sites in 1987, relative to the first time tree condition was assessed in 1984 or 1985. However, with the reoccurrence of the forest tent caterpillar and the hot, dry summers of 1988 and 1989, general tree condition deteriorated at all but the Thunder Bay site subsequent to 1987. Tree mortality by the 1989 assessment year was highest at the Magnetawan and Etwell study sites, the same sites with the lowest over-all tree starch reserves.

9.8.1 Starch Levels, Defoliation and *Armillaria mellea*

Trees which have been defoliated must draw on their stored starch reserves to produce a second crop of leaves and to carry on with other necessary metabolic activities. Severely defoliated trees may have root starch levels of about 1/10 of non-defoliated trees, perhaps as low as 1% or less, which is about 1/3 of the minimum level necessary for normal metabolic activity.[115] Therefore defoliated trees experience a critical energy shortage and must defer some activity, typically seed production, incremental growth, repair and maintenance, and protective chemicals, and channel the available energy into life-sustaining activities, which are primarily root and foliage production.

Trees which have been defoliated are more susceptible to infection by *Armillaria mellea*.[116] This root rot fungus may actually be more aggressive on weakened trees.[116] Trees store energy in the form of starch, but the starch must be converted to sugar in order to be used by the tree. In addition to having lower overall root starch reserves, defoliated trees are characterized by higher root sugar concentrations.[85] This indicates that the starch that is present in the roots is in a state of flux, continuously being converted to sugar for use elsewhere in the tree. *Armillaria mellea* is better able to colonize substrate high in sugars than those of starch. Also, lower tree vigour and lower levels of production of natural protective chemicals within the tree results in a significantly inhibited ability to resist fungal infection. Therefore, following defoliation, tree roots provide both a more attractive environment for the growth of root rot fungi and at the same time they are less able to defend themselves against fungal spread once infection has occurred.

Armillaria mellea infection initiated by defoliation may result in a secondary or delayed decline phase. The first decline wave occurs during or immediately following defoliation. In this phase, mortality occurs on poor vigour trees as a direct result of severe and repeated defoliation. Generally, trees that are more than 50% defoliated for two or more consecutive growing seasons are at risk of mortality, particularly if the trees have inherent poor vigour or experience concurrent environmental stress. During and subsequent to defoliation, *Armillaria mellea* spreads rapidly into the weakened trees. After several years of stability or even apparent stand improvement, the *Armillaria mellea* infected trees begin to show decline symptoms and the second or delayed decline phase occurs. Decline and/or mortality at this time is often referred to as "mysterious" or "unknown" because it is not obviously related to an observable cause. Environmental conditions that impose additional stress on the forest, such as adverse climate, air pollutants and poor stand management, will exacerbate the second decline phase. Under these circumstances, *Armillaria mellea*, which is usually considered a secondary pathogen, may actually be a primary pathogen, thereby shifting from a contributing factor to an inciting factor in localized forest decline.

All of the Muskoka region study plots and the Thunder Bay site have experienced severe and repeated defoliation (the Thunder Bay plot may not have been defoliated as severely but has suffered with a chronic forest tent caterpillar presence). Defoliation, in conjunction with concurrent and subsequent climate and pollution stresses, would have created ideal conditions for *Armillaria mellea* infection. *Armillaria mellea* was likely a significant factor in sugar maple mortality in the Muskoka region in the early 1980s following the forest tent caterpillar infestation of the late 1970s. Considering the degree of climate stress in the late 1980s, combined with the reoccurrence of forest tent caterpillar in 1987-89, higher than normal tree mortality associated with *Armillaria mellea* is likely to occur on some sites again in the early 1990s.

9.9 Dendrochronology

Growth is the cumulative result of all factors acting on the tree over time. Some factors, such as tree species, tree genetics, and site quality, are fixed and therefore exert a relatively constant influence on the resultant tree growth. Stress factors, such as climate, insects and disease, tree competition, and air pollutants, can change dramatically with time and contribute to in radical growth fluctuations. Trees are perennial life forms, and so exposure to chronic stress may have a potentially cumulative effect on growth.

Forests are dynamic ecosystems in which only a relatively few individuals survive to maturity. Forest growth is strongly influenced by nutritional availability. Growth may be stimulated by increased N supplied through acidic deposition, or growth may be retarded as the same acidic deposition accelerates base cation leaching from soil, resulting in nutrient deficiencies. The high species diversity of eastern hardwood forests enhances competitive interaction between species and increases the probability of competitive amplification of secondary stress from air pollutants.[78] There is also a considerable gradient of tree species sensitivity to air pollution. Under a chronic pollutant stress, genetic diversity would create a sensitivity gradient within species. The laws of random selection suggest that sensitive individuals would be randomly scattered throughout the forest. Therefore, under sub-acute pollution loadings, increased mortality may first occur in scattered, isolated pockets among the most sensitive trees. This is precisely the geographic pattern of decline observed with sugar maple across Ontario. Even though the occurrence of decline is more frequent in specific areas of the province (mostly the southcentral Parry Sound/Muskoka region) the severity of decline within these areas is very patchy. The flaw in this hypothesis is that, based on controlled environment experiments, sugar maple is considered to be intermediate or even quite tolerant to most "conventional" air pollutants, such as ozone, SO_2, and fluoride, and relatively tolerant to acidic deposition, based on laboratory germination and seedling trials.[73] However, preliminary results of an investigation into the genetic diversity of sugar maple trees in the Muskoka and Peterborough study regions indicated that declining trees were less genetically diverse (more in-breeding) than healthy sugar maple trees. This would suggest the possibility of genetic predisposition in the declining tree population, in that the trees with less genetic variability are less flexible in their response to stress factors and therefore are more likely to develop decline symptoms.

Forest productivity, usually measured as the volume of stem wood produced per unit area at a given age, is relatively constant over a wide range of tree densities (i.e., total volume of a large number of small trees/ha would be similar to the volume of a fewer number of large trees/ha). Therefore, pollution-induced growth inhibition or even mortality of randomly-distributed, genetically-susceptible trees are not likely to affect the productivity of the forest as a whole unless the percentage of affected trees becomes so large that the forest becomes seriously under stocked.[124] Therefore, the true impact of air pollution is virtually impossible to quantify. If mortality is occurring on pollution-sensitive trees, growth of the residual pollution-resistant trees may improve as a result of their improved competitive advantage, making it difficult to measure an effect on overall forest productivity.

Nonetheless, relative growth rates of individual trees can be examined with dendrochronological methods. Dendrochronology is the study of tree rings and their relationship with historical events. Tree rings have been used to date insect and disease outbreaks, forest fires, floods and other natural catastrophes.[26, 43, 59, 106] Dendrochronology has even been used to attempt to date ice islands, volcanic eruptions, and paintings.[60, 88, 119] The effects of point sources of air pollution also have been documented by tree ring studies.

Dendrochronological methods were used in the sugar maple etiology study to determine 1) if the tree ring data can identify a point in time at which the current maple decline episode was initiated, and 2) if there has been a change in the long term growth rate of sugar maple corresponding to the period of increasing atmospheric pollutants. Tree rings can be reliable indicators of historical environmental conditions because carbon allocation for stem xylem growth is fourth in line after foliage, shoots, and roots. Simplistically, when environmental conditions are favourable for growth and the stress levels are low, then there is adequate energy remaining after foliar, shoot and root development. This extra energy is provided for stem xylem growth, resulting in wider annual tree rings. When environmental conditions are poor, or stress levels are high, all available energy is channelled into root and foliar production, leaving relatively little for stem xylem growth, resulting in narrower annual tree rings.

Two dendrochronological methods were used in this study, increment cores and whole tree stem analysis.

9.9.1 Increment Cores

Two increment cores were extracted from each of the six trees used for extensive foliage, root and soil sampling at each of the 11 study sites. These trees represented the decline gradient encountered at each site. An increment core is about the diameter and length of a drinking straw, and is extracted from the radial plain of the tree trunk. The annual growth rings from the bark to the centre of the tree can be examined and growth patterns interpreted. Two increment cores (one from the north and one from the south side) were collected at breast height from each of the sample trees, placed in plastic drinking straws, and frozen until preparation for measurement. The cores were mounted on plywood boards and sanded until the rings were clearly visible. Phluoroglucinol was used, when staining was required, to highlight particularly faint rings.

Despite an elaborate core preparation, the diffuse porous, extremely fine and uniform-grained structure of sugar maple xylem resulted in about 10% of the cores having sections where the rings were too obscure to be measured with confidence. These cores were discarded. The remaining cores were then sorted as to the clarity of the annual rings. The cores with the clearest rings were measured first and used as quality control bench marks, against which the less clear tree ring series could be compared.

The increment cores were measured to 0.01 mm on a Bannister Incremental Measuring Machine interfaced with a microprocessor. Accompanying software, modelled after similar systems in use by the MNR, provided on-line graphics of the tree ring chronologies so that the cores could be continuously compared with the bench-mark data series to ensure accurate tree ring cross-dating.[23]

All other factors being equal, annual tree ring width generally tends to decrease with increasing tree age. As the tree gets older, it's circumference increases and the rings are laid down over a constantly increasing bole, therefore equal amounts of growth appear proportionately narrower. It is necessary to filter out this effect of tree age and other natural growth regulators, such as climate and competition, before the impact of anthropogenic stresses such as air pollutants can be evaluated.

Statistical smoothing functions designed to remove the tendency towards narrower tree rings with increasing tree age have been developed. The function used to "de-trend" the tree ring series from this study was an orthogonal polynomial. This function fits a regression curve to each raw ring series and divides the actual ring width by each yearly value of the fitted curve. The resultant tree ring chronology has a mean approximating 1.0 and a variance that, in theory, is independent of tree age, position within the stand, and mean growth rate of the tree.[40, 41] The indexed tree ring values usually range from 0 to 2, and therefore have a magnitude similar to the actual ring widths in mm. However, the indexed values are not true ring widths, they are mathematical interpretations of ring width, and so are unit-less.

This function has a significant limiting factor in that it assumes a specific relationship with time and forces the data through the transformation. Subtle reductions in tree growth, from whatever cause, may be "seen" by the function as an age-related response and be filtered out of the resultant chronology, thereby biasing the data against non-age-related growth reductions. An advantage of the function is that it standardizes the data, which was important in this study because of the variation in growth rates related to the difference in site quality of the 11 plots.

When studying the effects of a point source of air pollution on tree growth the growth variability due to climate can be filtered out by comparing the tree chronologies with those from control sites that are outside the pollution deposition zone but close enough to share a common climate regime. However, acidic deposition is a regional pollutant that can affect large areas, thereby making it very difficult, if not impossible, to locate control sites for tree growth studies. Therefore, even though the tree rings can be measured with considerable accuracy and the data de-trended to minimize the geometry associated with tree age and stand competition, the effect of climate may be significant and remains largely unquantifiable.

In this study the two individual increment cores from each tree were measured and the data combined to form a mean tree ring series for each tree. The average tree chronology was transformed into indexed ring values with the de-trending function. The decline gradient at each site was examined in order to cleanly stratify the growth chronologies according to decline class. The chronologies from the trees with the two lowest decline indices (healthiest) and the two highest

decline indices (most declining) were combined to provide chronologies for healthy and declining trees respectively for each site. The indexed growth chronologies of the two remaining trees at each site, those that were in between in decline condition (neither truly healthy nor in an advanced state of decline), were not used for the growth comparisons, except as a replacement tree for increment cores that could not be measured with confidence.

The tree growth chronologies for healthy and declining trees from each of the 11 study sites are illustrated in Figures 15 through 25. The chronologies are very similar for the healthy and declining tree classes at each site. This was expected, as the trees were chosen to be similar in age, site quality, and position within the stand. The impact of defoliation on sugar maple growth is clearly evident at all the Muskoka plots. Reductions in growth occurred at most sites during the peak insect defoliation periods of the 1940s, 1950s, and 1960s, and at all Muskoka sites during the epidemic of the late 1970s. This particular epidemic was concurrent with three consecutive climate stress years (1976, 1977, and 1978) and a four year spring drought (1975 to 1978). The combined defoliation and climate stress was unquestionably the inciting decline factor at the Magnetawan (Figure 15), Etwell (Figure 18), Musquash River (Figure 19) and Utterson (Figure 20) study plots. The healthy and declining tree growth chronologies at these sites both plummeted in the late 1970s. Subsequent to the collapse of the insect population the healthy trees recovered, whereas the growth of the declining trees continued to deteriorate.

The late 1970s was also the time at which the growth of the healthy and declining trees diverged at Cecebe Lake (Figure 17), Horn Lake (Figure 16), Point Ideal (Figure 22), and Swan Lake (Figure 21). However, at these Muskoka study plots the growth of the declining trees recovered marginally from the low point in late 1970, but subsequent to 1980 the growth consistently deteriorated. It is possible that at these four sites the trees were significantly weakened by defoliation and adverse climate, but a post-stress aggressive _A_. _mellea_ infection actually incited the "second phase" decline.

Swan Lake was the Muskoka-area plot that was least affected by the 1970s combination of defoliation and climate stress. The magnitude of growth reduction was less in the declining trees sampled at this site than the other Muskoka plots, and although the growth recovery at Swan Lake was significant, it did not achieve the same level as the healthy trees.

Although the annual insect and disease surveys indicated that tent caterpillar defoliation had occurred in the Peterborough area it is apparent from the growth chronologies in Figures 23 (Woodview) and 25 (Indian River) that the defoliation was not nearly as severe as was experienced in the Muskoka area. The Woodview site appears to have been defoliated in the 1940s, the 1950s and the 1970s, but likely escaped significant defoliation in the epidemic that occurred in the mid 1960s. By comparison, the Indian River site may have received marginal defoliation stress in the 1940s and 1960s epidemic but appears to have escaped the outbreaks that occurred in the 1950s and the mid-to-late 1970s. Climate and site have likely played a larger role in the Peterborough area than at the Muskoka sites. Thirteen of the 20 significant climate stress events and 10 of the 15 climate stress years have occurred in the last two decades in Peterborough. At Woodview, 1977 was the year in which the chronologies diverged and the growth of the declining trees deteriorated sharply. This site is characterized by very shallow soil, and therefore, it would have been particularly susceptible to root mortality associated with the very low winter temperature and record low snowfall

of the winter of 1976/77. This was followed by a very dry spring, which would have exacerbated the moisture shortage and inhibited root recovery. Even though 1977 appeared to be the critical year at Woodview, the growth of both the declining and healthy trees at this site had been in a general decline trend since the early 1960s, thereby suggesting that factors in addition to climate were contributing to poor tree vigour at this study plot for at least 20 years.

The Indian River study site is located on drumlinized till with deep fine textured soil and has a spring that flows from the slope near the plot. Therefore it would be less susceptible to drought and root mortality associated with freezing soil than the Woodview plot. The cold, dry, climate stress events of 1977 did not appear to adversely affect the growth of the healthy trees at Indian River. However, the growth of declining trees, which had been relatively stable but depressed since the mid 1960s, continued to decline every year subsequent to 1977.

Unlike the Muskoka and Peterborough area plots, the growth chronologies derived from indexed ring values from the Thunder Bay (Figure 25) study site do not identify a specific time at which the growth patterns of the healthy and declining trees diverged, thereby providing few clues as to associated causal factors. Although this area has endured a chronic forest tent caterpillar presence for the last 15 years, it has not appeared to have affected the declining tree population more severely. Figure 25 illustrates that the growth of the declining trees deteriorated sharply in 1983 and 1984 while the growth of the healthy trees increased. This suggests that the causal decline factors are more recent than those implicated in the other two study regions. Although it is likely that sugar maple in Thunder Bay, by virtue of it's northern location, is more cold tolerant, the cumulative effect of frequent climate stress events and chronic, although rarely severe defoliation, cannot be ignored as possible contributing factors to the moderate decline observed at Thunder Bay.

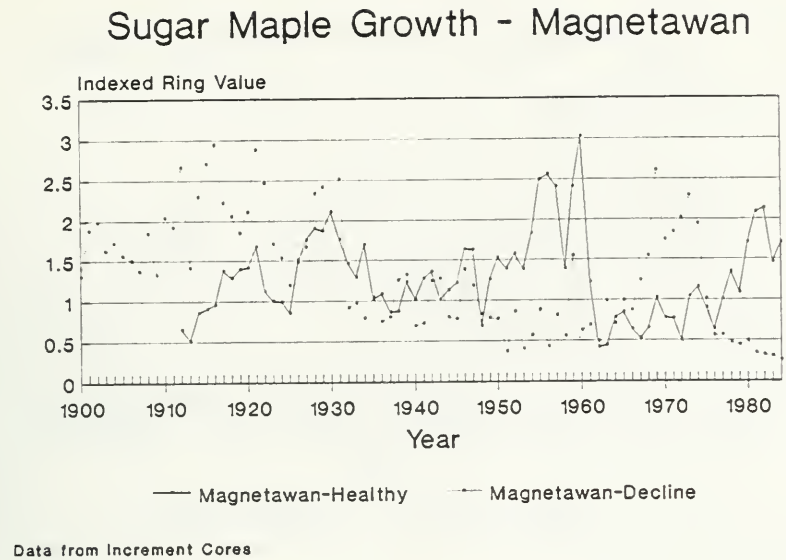


Figure 15
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Magnetawan
(Indexed Ring Values - Increment Cores).

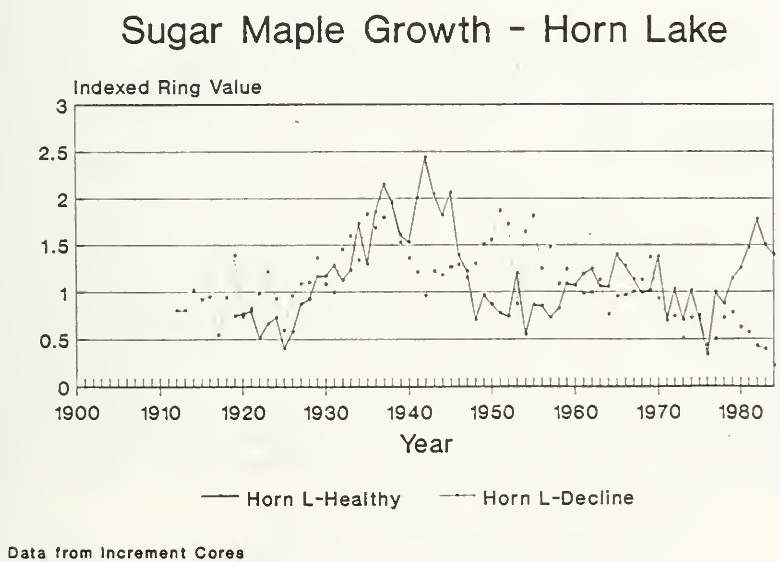


Figure 16
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Horn Lake
(Indexed Ring Values - Increment Cores).

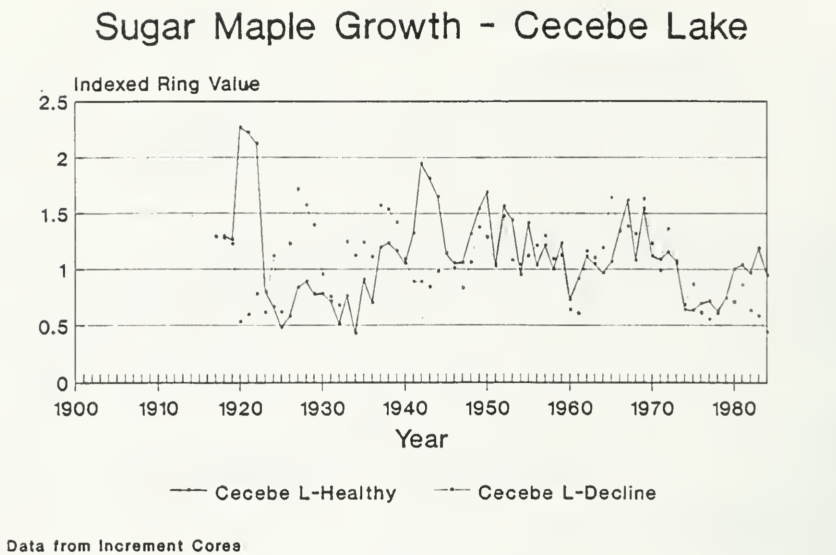


Figure 17
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Cecebe Lake (Indexed Ring Values - Increment Cores).

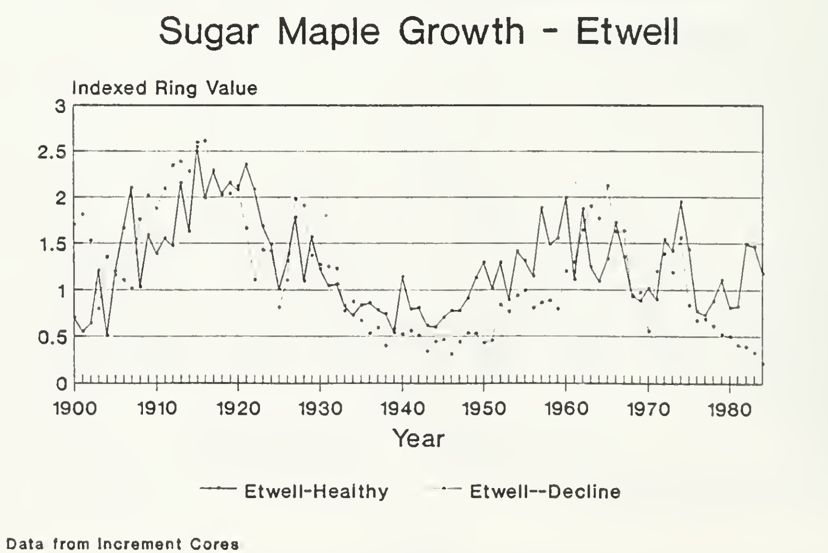


Figure 18
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Etwell (Indexed Ring Values - Increment Cores).

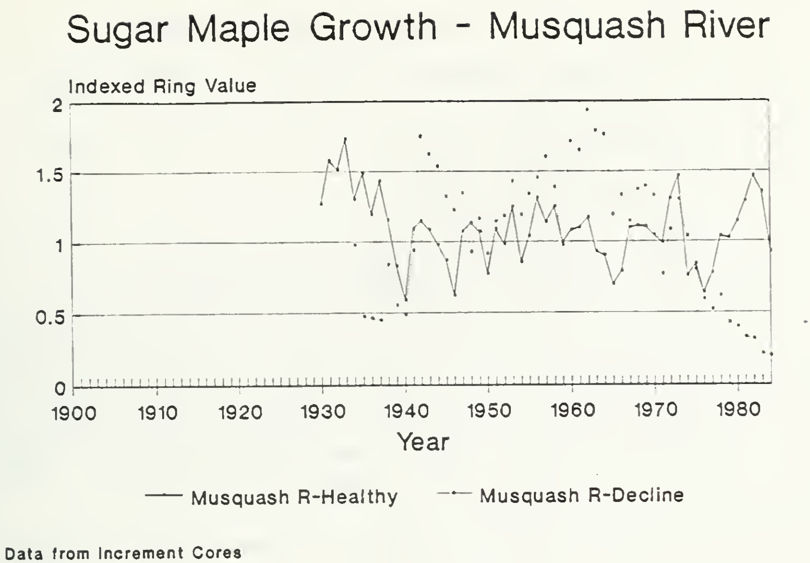


Figure 19
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Musquash River (Indexed Ring Values - Increment Cores).

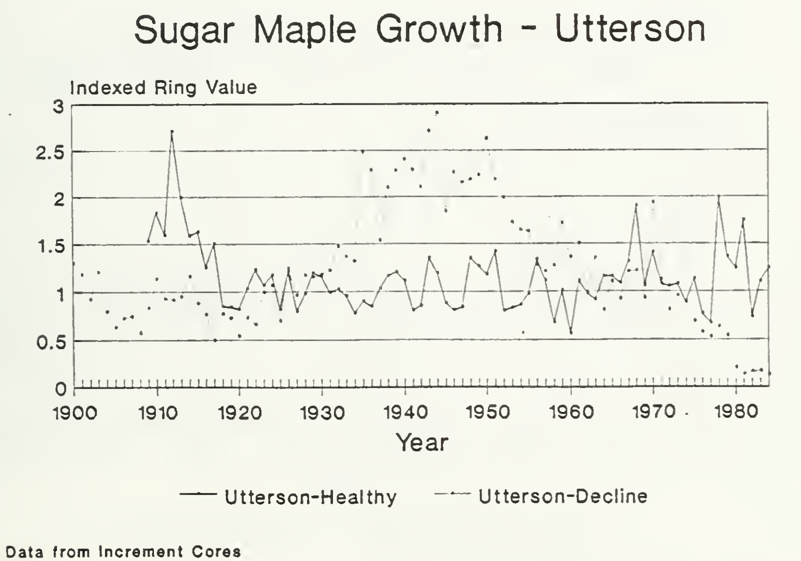


Figure 20
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Utterson (Indexed Ring Values - Increment Cores).

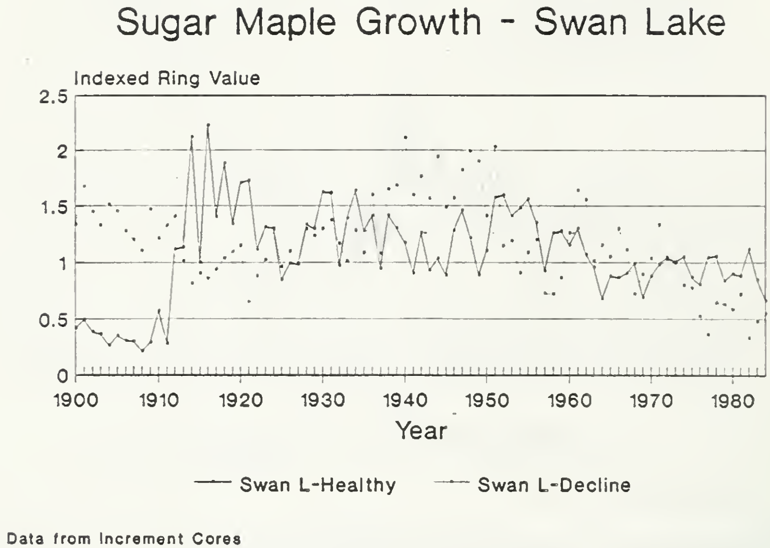


Figure 21
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Swan Lake (Indexed Ring Values - Increment Cores).

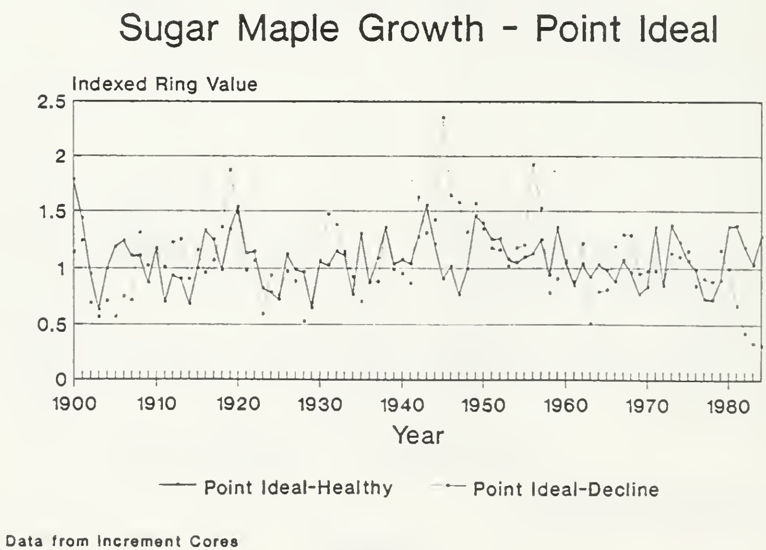


Figure 22
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Point Ideal (Indexed Ring Values - Increment Cores).

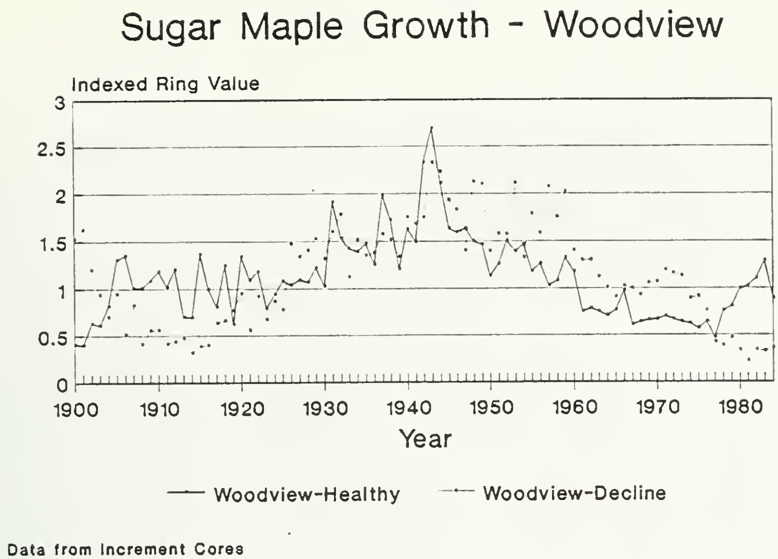


Figure 23
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Woodview (Indexed Ring Values - Increment Cores).

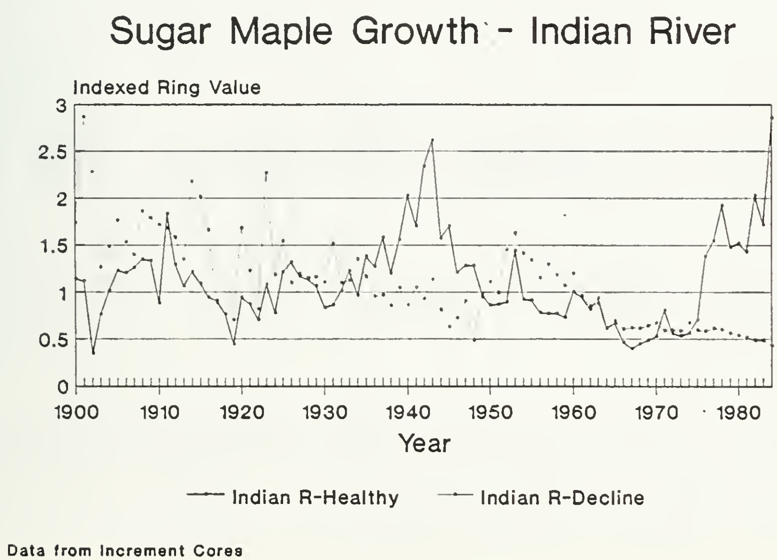


Figure 24
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Indian River (Indexed Ring Values - Increment Cores).

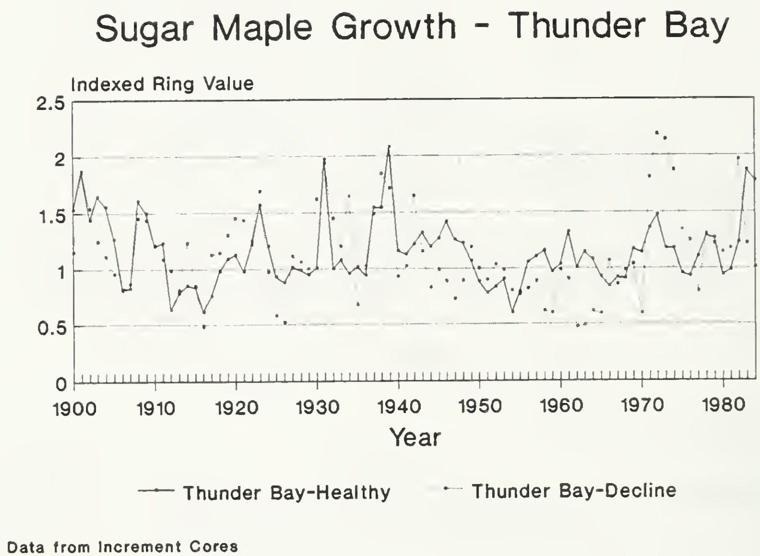


Figure 25
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Thunder Bay (Indexed Ring Values - Increment Cores).

9.9.2 Stem Analysis

Stem analysis was the second method used in this study to examine the growth patterns of sugar maple. Two trees were selected from the six original sample trees at 8 of the 11 study plots. Four trees were selected for stem analysis at Thunder Bay and Swan Lake. Utterson was the one plot omitted. The selected trees were stratified as to decline class, i.e., healthy and declining trees were sampled at each site, similar to the selection procedure used for the increment cores. Because there were fewer trees included in the stem analysis part of the study, greater care was taken to match the healthy and declining trees in each plot relative to site quality, age, and position within the stand.

The trees were felled and disks removed from the stem and main leader at intervals of 1 m from the stump (35 cm) to the top of the tree. At the two sites where four trees were sampled, the replicated trees were sampled at 2 m intervals. The tree disks were prepared in the Phytotoxicology dendrochronology laboratory and the annual growth rings on the north and south radii were measured to 0.01 mm on a microprocessor-driven TRIM system. The TRIM system was developed by the Ontario Tree Improvement and Forest Biomass Institute at the MNR research centre in Maple.[23, 24] Ring width data for each disk were compiled and a variety of volumetric data were calculated for each tree.

One of the most diagnostic volume parameters acquired through stem analysis is Specific Volume Increment, commonly abbreviated to SVI. The SVI is calculated by dividing the wood volume produced over the entire main stem each year by the surface area of the corresponding annual growth ring. It can be equated to the overall average annual ring width calculated over the entire height of the tree. Traditionally, tree rings have been measured from increment cores collected at breast height (1.3 m) or at the stump after the tree has been felled. However, the width of the annual growth ring is not uniform along the entire vertical axis of the tree. In fact, for any given year, the width of the annual xylem layer increases from the apical meristem to a maximum in the area approximating the centre of the crown, then decreases substantially along the trunk and increases again near ground level.[18, 83] This pattern seems to be more accentuated in softwoods and somewhat less in hardwoods.[25] Therefore, measurements of annual ring widths taken at breast height or on the stump may under or over estimate actual annual growth, respectively. SVI would appear to have the potential to overcome the inherent variability of annual rings within the tree because it is calculated from measurements made along the entire height of the tree. However, SVI is not a parameter that is widely used in dendrochronological research, likely because of the requirement for specialized microprocessor technology, the destructive nature of the sampling, and the significant time required for sample preparation and measurement. Although limited research has been conducted, SVI has been shown to be similar to ring series collected at breast height for sugar maple.[22]

It is uncertain how SVI reflects the geometry of tree age, i.e., if it is susceptible to the same tendency towards reduced width with increasing tree age as are ring series collected from breast height measurements. Therefore, it is uncertain if SVI chronologies should be smoothed or de-trended, as were the increment core data in Section 9.9.1. Experience at the MOE dendrochronology laboratory, and the limited literature, have confirmed SVI to be a very sensitive indicator of the response of the tree to changes in it's environment, and that long SVI chronologies from old trees

appeared to respond proportionately as well to environmental stimuli as did chronologies from young trees. Therefore, the SVI data compiled for this report have been examined in the raw, unfiltered state.

Table 31 summarizes the mean SVI for 10 of the 11 study plots for the period 1900 to 1984. The average growth of sugar maple was marginally higher in the Muskoka area than Peterborough. The growth of sugar maple at the Thunder Bay plot was considerably less than the two southern study regions. This was unquestionably related to the northern location and proportionately shorter growing season. Within regions, the average growth was slightly better at Woodview relative to Indian River in Peterborough. In the Muskoka area, average growth tended to be higher at Musquash River, similar at Magnetawan, Horn Lake, Cecebe Lake, Etwell and Point Ideal, and marginally lower at Swan Lake. Absolute comparisons of growth can be made with the SVI data because it has not been mathematically transformed. This could not be done with the increment data, at least not for the entire length of the chronology, because it had been normalized by transformation through an orthogonal polynomial such that the average tended towards an absolute value of 1.0. However, comparisons of subsets of the increment data are acceptable.

Table 31 also summarizes the growth rates relative to decline classification to determine if the declining trees had poorer growth rates relative to the healthy trees at each plot over the entire life of the trees. This may indicate inherently poorer vigour in the declining trees, perhaps of genetic origin. Of the seven plots in the Muskoka region, only at Horn Lake and Etwell did the declining trees have significantly poorer average growth rates. In contrast, declining trees (trees that were in a state of decline in 1984) at Cecebe Lake and Swan Lake had significantly higher average growth rates than healthy trees over the long term. Similarly, declining trees averaged significantly poorer growth at Indian River and better growth at Woodview and Thunder Bay. Therefore, predisposition towards decline as a result of genetically inherent poorer tree vigour was not a ubiquitous condition, but it may have been a complicating factor at Horn Lake, Etwell, and Indian River.

The SVI growth chronologies for each of the study plots are illustrated in Figures 26 to 35. The slope of the SVI curves vary more through time than the curves produced from the indexed increment core data because the SVI chronologies are not normalized. Also, the reductions in growth corresponding in time to epidemics of defoliating insects appear to be more substantial in the SVI chronologies than the increment core curves. The greater slope variability and the dramatic fluctuations in amplitude suggest that SVI may be more responsive than increment cores to specific environmental events.

The impact of defoliation during the four major forest tent caterpillar epidemics is clearly evident in the growth chronologies from the Muskoka area plots. At all these sites the growth of both healthy and declining trees was severely inhibited by defoliation in the 1930s and 1950s, although growth recovery occurred in both condition classes. At Horn Lake and Musquash River the declining trees did not recover after the 1960s epidemic, but began a progressive growth decline that continued through to the sampling in 1984. The growth of declining trees lagged significantly behind the healthy trees after the 1960s epidemic at Etwell and Cecebe Lake but had recovered to near-predefoliation levels by the mid 1970s, at which time they were significantly stressed again by another tent caterpillar outbreak. The declining trees did not recover from the 1970s defoliation. At Point Ideal the declining and healthy tree chronologies were very similar throughout the last 60 years.

Table 31
Mean Specific Volume Increment of Healthy and Declining Sugar Maple Trees from 10 of the Study Sites.

Study Site	Mean SVI (mm): 1900 - 1984 Trees Combined*	Healthy Trees	Declining Trees	% Difference H vs D**	p<
Magnetawan	1.57	1.67	1.47	-12.0	ns
Horn Lake	1.61	1.83	1.42	-22.4	.01
Cecebe Lake	1.43	1.39	1.68	+20.9	.01
Etwell	1.34	1.54	1.14	-26.0	.01
Musquash R.	1.93	2.04	1.83	-10.3	ns
Point Ideal	1.32	1.27	1.37	+7.9	ns
Swan Lake	1.09	0.98	1.19	+21.4	.01
Muskoka Mean	1.43	1.46	1.40	-4.1	ns
Indian R.	1.30	1.40	1.20	-14.3	.01
Woodview	1.51	1.23	1.79	+45.5	.01
Peterborough Mean	1.40	1.32	1.49	+12.9	.05
Thunder Bay	0.98	0.85	1.11	+30.6	.01

* mean growth rate, healthy and declining trees combined.
** growth of the declining trees expressed as a percentage of the healthy tree growth.
ns - not significant (p>0.05).

At this site it was not until the defoliation of the 1970s that the growth curves diverged and the declining trees did not recover. The SVI chronology for Swan Lake is inconclusive in regards to identifying a point in time at which the tree decline begins.

The Magnetawan SVI chronology is unique in the Muskoka plots in that the growth was severely suppressed up until the mid-1930s. This was probably related to oppressive competition from mature overstorey trees. Release, likely in the form of a heavy cut, occurred in about 1936 allowing the understorey trees to increase growth dramatically.

The SVI chronologies from the two Peterborough plots indicate that the growth of the declining trees had been progressively deteriorating for the last three or four decades. Even the growth of the healthy trees at Woodview had been remarkably subdued in the last 20 years and had only recently begun a trend towards improvement. There is no evidence of growth response to release from competition at this site even though the bush has been cut regularly and quite heavily. In contrast, the growth of healthy trees at Indian River has been quite robust. The SVI data from the Peterborough plots suggest that longer term regional stress factors, such as climate, air pollution, management, and possibly genetics (at Woodview) may have contributed to the recent decline.

The SVI chronology for Thunder Bay, like the increment core data, does not indicate a point in time at which changes in growth may relate to observed decline symptoms. The SVI curve does, however, appear to be more illustrative of defoliation effects, although tree decline status is not correlated with insect stress. The four major depressions in the SVI curve correspond well with historical tent caterpillar outbreaks, as illustrated in the growth curves from the Muskoka-area plots. However, the FIDS reports do not confirm that this insect was present in high numbers in the Thunder bay area at these times. The SVI curves for both healthy and declining trees do indicate a trend towards reduced growth commencing about the mid-1960s with minimum growth levels occurring in the 1980s. The 1980s were a period of climatic extremes that unquestionably has inhibited sugar maple growth and contributed to decline of less vigourous trees at the Thunder Bay study plot.

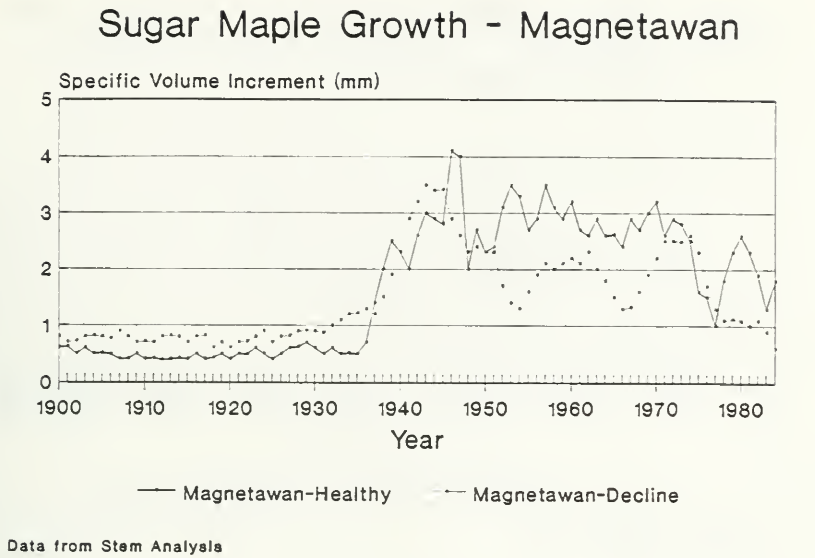


Figure 26
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Magnetawan (Specific Volume Increment - Stem Analysis).

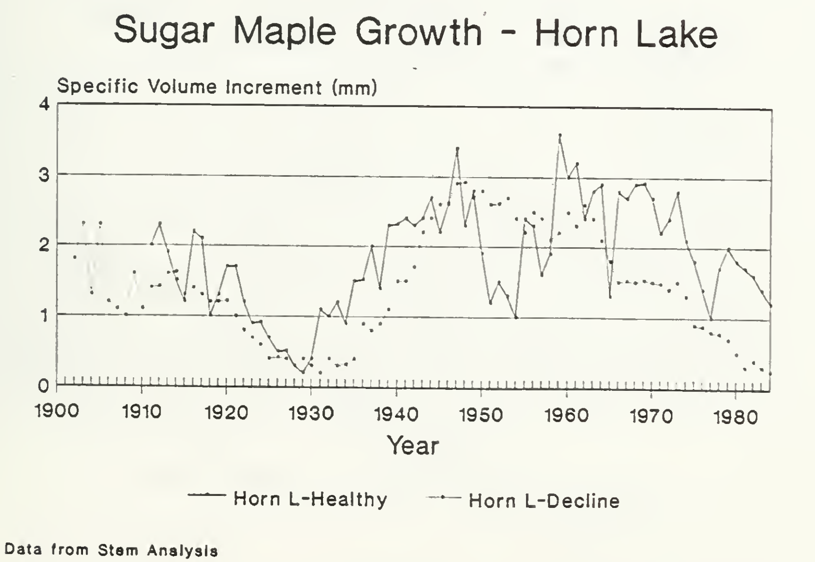


Figure 27
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Horn Lake (Specific Volume Increment - Stem Analysis).

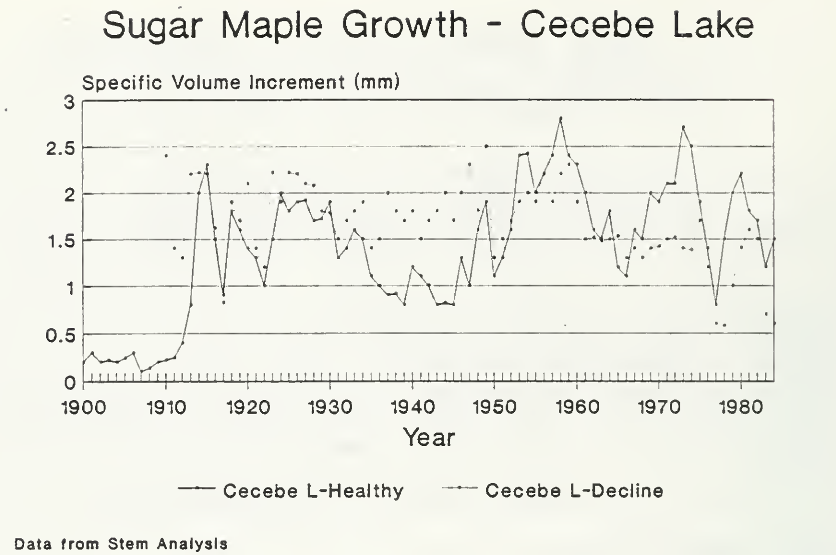


Figure 28
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Cecebe Lake (Specific Volume Increment - Stem Analysis).

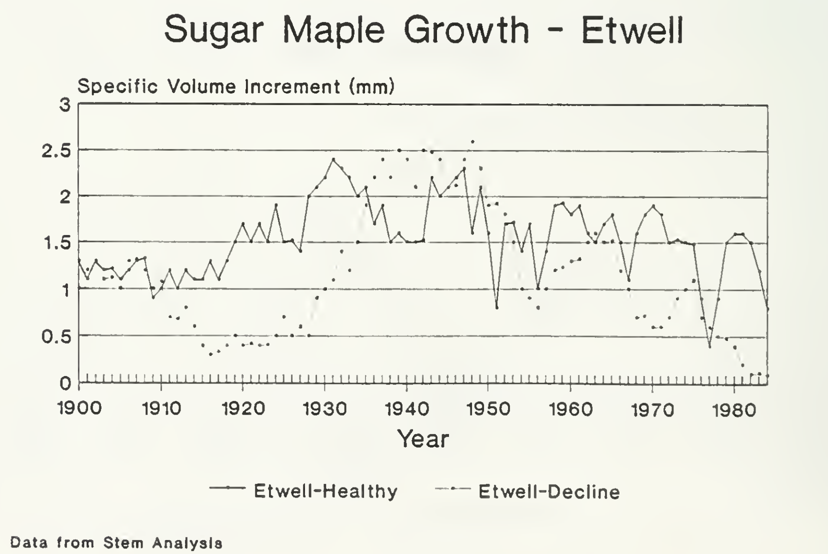


Figure 29
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Etwell (Specific Volume Increment - Stem Analysis).

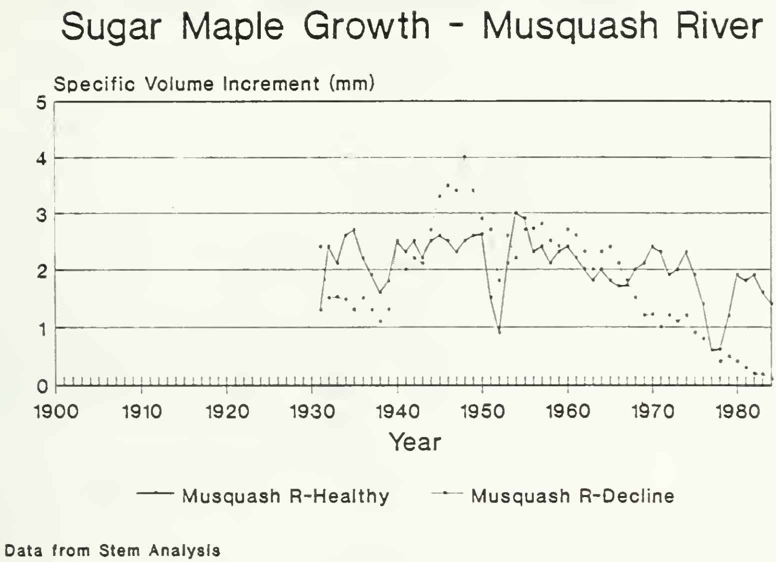


Figure 30
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Musquash River (Specific Volume Increment - Stem Analysis).

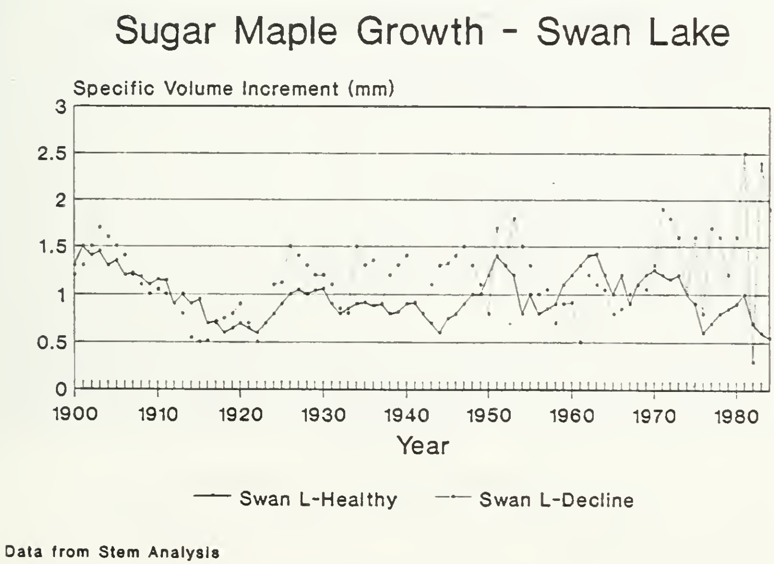


Figure 31
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Swan Lake (Specific Volume Increment - Stem Analysis).

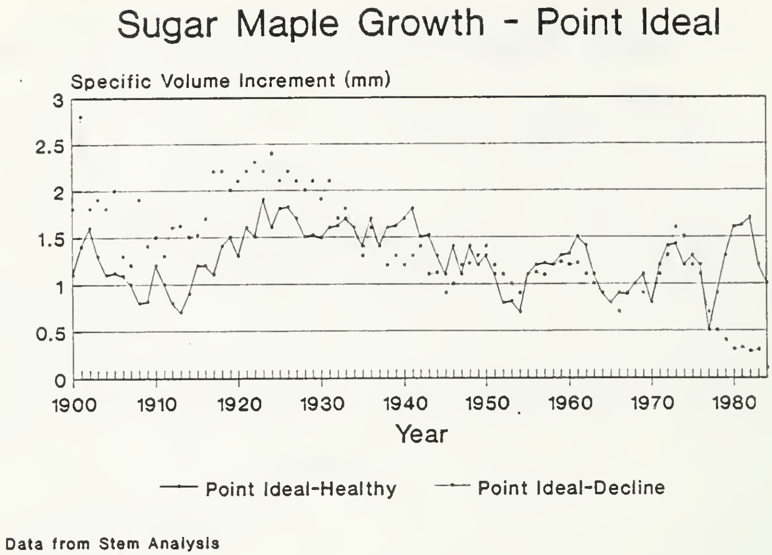


Figure 32
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Point Ideal
(Specific Volume Increment - Stem Analysis).

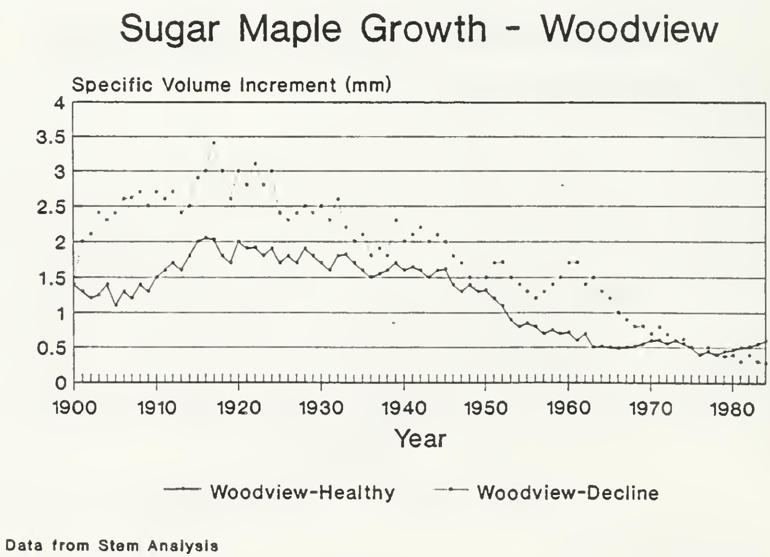


Figure 33
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Woodview
(Specific Volume Increment - Stem Analysis).

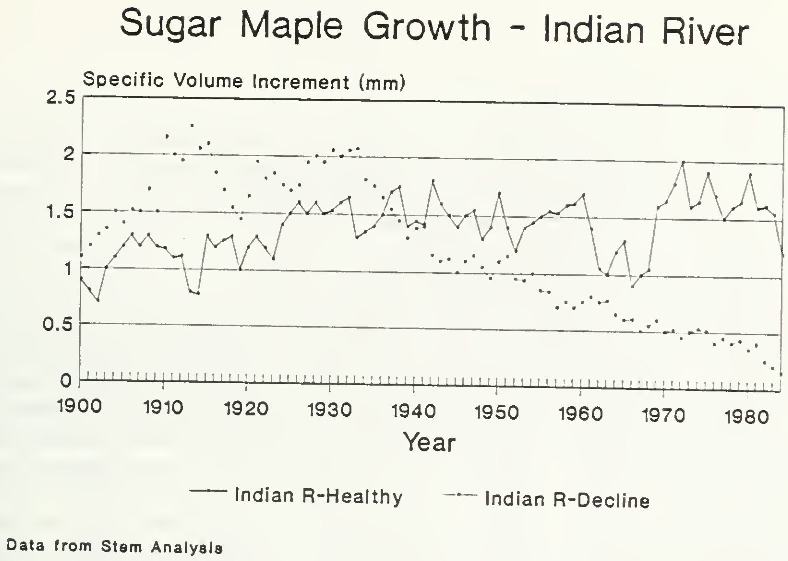


Figure 34
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Indian River (Specific Volume Increment - Stem Analysis).

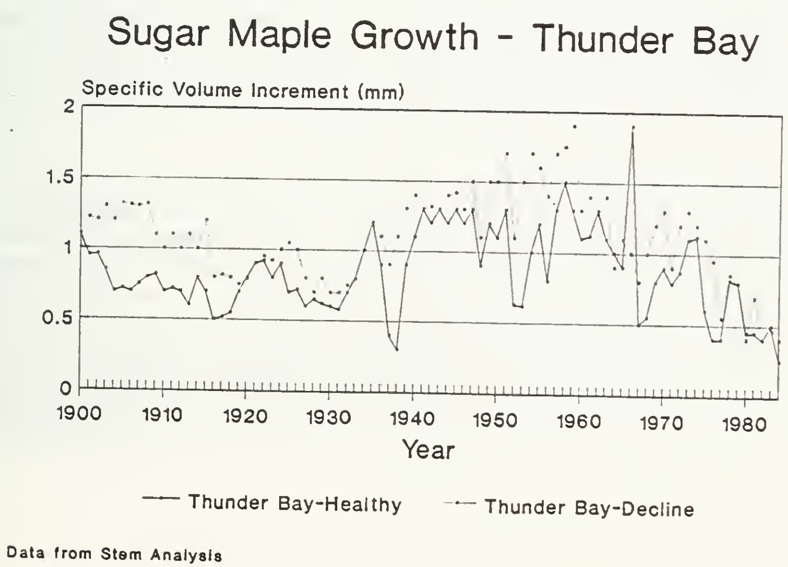


Figure 35
Sugar Maple Growth Chronologies of Healthy and Declining Trees at Thunder Bay (Specific Volume Increment - Stem Analysis).

9.9.3 Comparison of Long-Term Tree Growth

Forest decline need not only imply tree death. A sustained reduction in the rate of annual radial growth may occur in the absence of crown symptoms usually associated with forest decline. A reduction in annual incremental growth not associated with age or normal stand dynamics indicates a reduction in overall tree vigour and therefore may be the first signs of potential or impending forest decline. Reductions in growth on a regional scale of red spruce, yellow pine, balsam fir, oak, and maple have been documented in the east and northeast U.S.[1, 55a, 56, 79, 95] In these areas the cause(s) of the growth decline could sometimes be related to climatic events, particularly drought, but growth recovery subsequent to the drought lagged significantly or did not occur. In some cases, trees showing symptoms of decline experienced a shift towards reduced growth 20 or 30 years before visible symptom development. It has been suggested that the relationship of tree growth to climate may be altered by a regional-scale stress associated to atmospheric pollutants.[89] Reductions in tree growth have been reported, and the reductions have occurred concurrent with an increase in the levels of atmospheric pollutants and in areas where ambient pollution and pollutant deposition are high.

The tree growth data obtained from the Ontario sugar maple etiology study was examined to determine if there has been a recent trend towards reduced incremental growth. The growth data were aggregated into two 30 year time periods. The first period, 1901 to 1930, was selected to represent a time when atmospheric pollutant levels in Ontario were much lower than present. The second period, 1955 to 1984, represents the period of highest pollution deposition in this century. The 1940s was a period of considerable industrial activity in Ontario and pollution levels were likely quite significant. Although the environmental impact in the 1940s would have been less than that of the most recent 30 year period, it certainly would have been greater than in the first 30 years of this century. Therefore, the time surrounding the 1940s was excluded in order to insure that the two time periods used for growth comparisons represented a low and a high deposition regime. Spreading out the comparative time periods was also done because some of the potential pollution-related growth inhibiting factors are associated with changes in soil chemistry and may require an extended period of deposition before effects are observed. In addition, 30 years was considered the minimum time period necessary to detect growth trends in the presence of the considerable annual growth fluctuations characteristic of the hardwood forest ecosystem.

Table 32 summarizes the mean indexed ring values (increment core data) for the healthy and the declining tree populations from the 11 study sites for the two 30 year time periods. Although the indexing function used to transform the increment core data normalizes the ring widths such that the average ring value for the entire 84 year period would approach 1, absolute comparisons of shorter time periods, in this case 30 years, would be appropriate. In fact, this type of indexing function tends to smooth the radical growth fluctuations that can be associated with juvenile tree growth which could be a factor at some study sites in the first 30 year period. The difference in growth in the most recent 30 years was expressed as a percentage of the first 30 year period (i.e., 1955-1984 compared to 1901-1930) for both the healthy and declining trees at each site as well as the average for each of the three study regions. The percent difference was tested for statistical significance with a t test.

Table 32
Comparison of Long Term Growth Rates of Healthy and Declining Sugar Maple:
Indexed Ring Value - Increment Core Data.

Study Site	Healthy Trees 1901-1930	1955-1984	% Diff.	p<	Declining Trees 1901-1930	1955-1984	% Diff.	p<
Magnetawan	1.27	1.33	+4.7	ns	1.96	0.98	-50.0	.01
Horn Lake	0.78	1.07	+37.2	.01	0.96	0.88	-8.3	ns
Cecebe Lake	1.15	1.03	-10.4	ns	1.06	0.99	-6.6	ns
Etwell	1.60	1.28	-20.0	.01	1.72	1.03	-40.1	.01
Musquash R.	nd	1.06	nc	nc	nd	1.06	nc	nc
Point Ideal	1.03	1.06	+2.9	ns	0.98	0.97	-1.0	ns
Swan Lake	1.01	0.99	-2.0	ns	1.16	0.90	-22.4	.01
Utterson	1.31	1.13	-13.7	ns	0.89	0.93	+4.5	ns
Muskoka Mean	1.16	1.12	-3.4	ns	1.28	0.97	-24.2	.01
Indian R.	1.04	1.01	-2.9	ns	1.51	0.74	-51.0	.01
Woodview	1.01	0.85	-15.8	.05	0.82	1.01	+23.2	ns
Peterborough Mean	1.02	0.93	-8.8	ns	1.17	0.88	-24.8	.01
Thunder Bay	1.11	1.14	2.7	ns	1.13	1.09	-3.5	ns

% Diff. - per cent difference in tree growth in the most recent 30 years (1955-1984) relative to the first 30 years of the century (1901-1930).

nc - not calculated.

ns - not significant, $p>0.05$.

From the increment core data from Table 32, there was no significant difference in long term growth rates of either the healthy or declining trees at Thunder Bay. In the Peterborough area, healthy trees at Woodview and declining trees at Indian River experienced significantly reduced incremental growth in the last 30 years. In the same time period, the growth of declining trees in Muskoka was significantly lower at Magnetawan, Etwell, and Swan Lake, whereas the growth of healthy trees also had declined significantly at Etwell and improved significantly at Horn Lake. Horn Lake was the only study site that had a trend toward improved growth; at all other sites there was either no significant difference between the two time periods or a significant reduction in growth in the last 30 years.

Growth reductions were substantially larger in the declining tree population. This is not surprising since the growth chronologies of most of the declining trees illustrated an abrupt and sustained decrease in growth subsequent to the mid-1970s. Based on the increment core data, declining trees in Muskoka and Peterborough averaged 24.2% and 24.8% (respectively) less incremental growth in the last 30 years compared to the first 30 years of the century. The mean growth data for the healthy trees from the Muskoka and Peterborough study regions also indicated a trend towards reduced incremental growth, although these differences were not statistically significant.

Table 33 summarizes the difference in long term growth rates of the healthy and declining trees from 10 of the 11 study sites using the growth data derived from SVI. Although SVI is a very sensitive indicator of changes in tree growth, as illustrated by the response to defoliation, the SVI data have not been normalized and therefore the absolute differences are much greater than those derived from the indexed increment core data summarized in Table 32. For example, using indexed increment cores the annual xylem growth of healthy trees at Magnetawan averaged 4.7% greater in the most recent 30 years relative to the beginning of the century. However, using the non-normalized SVI data from Magnetawan, the growth increase over the same time period averaged about 408% (0.49 mm - 1910 to 1930 vs. 2.49 mm - 1955 to 1985, mean annual xylem width).

The SVI data are consistent with the increment core data for Thunder Bay, both methodologies reveal no significant difference between time periods for either tree condition class. The pattern of long term growth at the two Peterborough area plots is not consistent between the two growth assessments. The SVI method indicates that substantial and highly significant growth reductions have occurred in the last 30 years for the declining trees at both sites and for the healthy trees at Woodview, where as the recent growth of healthy trees at Indian River has increased. However, on average, the SVI of all sampled healthy trees in the Peterborough area has decreased by 28.3% in the last 30 years. The SVI of the declining trees has decreased an average of 67.4% over the same time period. The declining growth at the Peterborough sites is clearly evident in Figures 33 and 34.

Table 33
Comparison of Long Term Growth Rates of Healthy
and Declining Sugar Maple:
Specific Volume Increment - Stem Analysis Data.

Study Site	Healthy Trees 1901-1930	Healthy Trees 1955-1984	% Diff.	p<	Declining Trees 1901-1930	Declining Trees 1955-1984	% Diff.	p<
Magnetawan	0.49	2.49	+408.2	.01	0.77	1.74	+126.0	.01
Horn Lake	1.23	2.21	+79.7	.01	1.12	1.43	+ 27.7	.05
Cecebe Lake	1.05	1.86	+77.1	.01	1.88	1.45	-22.9	.01
Etwell	1.38	1.48	+7.2	ns	0.75	0.85	+13.3	ns
Musquash R.	nd	1.90	nc	nc	nd	1.46	nc	nc
Point Ideal	1.30	1.17	-10.0	ns	1.89	0.90	-52.4	.01
Swan Lake	1.01	1.01	0.0	ns	1.07	1.28	+19.6	ns
Muskoka Mean	1.06	1.73	+63.2	.01	1.21	1.31	+8.3	ns
Indian R.	1.23	1.51	+22.8	.01	1.75	0.55	-68.6	.01
Woodview	1.67	0.58	-65.3	.01	2.62	0.88	-66.4	.01
Peterborough Mean	1.45	1.04	-28.3	.01	2.18	0.71	-67.4	.01
Thunder Bay	0.74	0.84	-13.5	ns	1.02	1.09	+6.9	ns

% Diff. - per cent difference in growth in the most recent 30 years (1955-1984) relative to the first 30 years of the century (1901-1930).
nd - no data, some sampled tress less than 75 years old.
nc - not calculated.
ns - not significant, p>0.05

The SVI growth data for healthy and declining trees at the seven Muskoka area plots are characterized by extreme variation. Healthy and declining trees at Magnetawan and Horn Lake and healthy trees at Cecebe Lake have averaged large growth increases in the last 30 years, whereas declining trees at Cecebe Lake and Point Ideal have averaged significant growth reductions. The trend towards reduced annual xylem growth at the Muskoka area sites in the last 30 years was much less evident with the SVI data than with the indexed increment core data. In fact, on average, the SVI data suggest that the annual growth of healthy trees in Muskoka has been about 63% better in the last 30 years.

Separating the sampled trees into healthy and declining classes may not be appropriate in regards to examining trends in long term growth because the declining trees have exhibited decline symptoms only since the early or mid-1980s. Table 34 summarizes the long term growth rates at each of the study sites using the increment core data for combined tree condition classes. Similarly, Table 35 summarizes the long term growth data using the SVI derived from stem analysis. There was no significant difference in long term annual incremental growth of sugar maple at Thunder Bay for either method. Growth reductions in Peterborough in the last 30 years averaged 17.4% ($p<0.01$) using indexed ring values and 51.4% ($p<0.01$) using the SVI method. At the Muskoka study sites the indexed ring values indicated that there had been an average growth reduction of 15.4% ($p<0.01$). In contrast, the SVI method suggested that over the last 30 years the average growth of the Muskoka trees had increased by 34.5% ($p<0.01$). However, the average SVI value is skewed by the Magnetawan site that recorded a growth increase of 236.5%. If this site was excluded, the Muskoka mean SVI would be lowered to a statistically insignificant 15.2% growth increase.

Although the tree ring chronologies derived from the sampled trees were very useful in identifying the initiation of decline at each of the study sites they were inconsistent in regards to determining if the trend in long term growth rates had changed. There was concurrence between the two methods that growth had not changed in Thunder Bay and that there was a strong tendency towards reduced growth at both Peterborough sites. However, in Muskoka the indexed ring values suggested that annual tree growth at some study sites had not changed significantly or had declined moderately at other sites (although the average growth was down). This contrasted with the SVI data that indicated that growth had increased at all but one of the Muskoka sites.

Neither method of growth evaluation (indexed ring values or SVI) can be considered more correct, and both have inherent characteristics that limit their practical application. The indexed ring values derived from increment cores probably present a conservative measure of reduced growth because the orthogonal indexing function may "see" a pollution-caused growth reduction as the natural response to increasing tree age and stand closure, and therefore partially remove the trend. An indexing function that does not assume a specific geometric relationship, such as moving spline function, may prove more reliable for dendrochronological studies of eastern Canadian tolerant hardwoods. Alternative indexing functions of this nature are under review.[13] Methodologies using increment cores are preferred because the cores are easy to obtain, are non-destructive, and permit a relatively large number of trees to be sampled; therefore, the data are more representative and

Table 34
Comparison of Long Term Growth Rates of Sugar Maple,
All Tree Condition Classes Combined:
Indexed Ring Values - Increment Core Data.

Study Site	Indexed Ring Value 1901-1930	1955-1984	% Difference	p<
Magnetawan	1.70	1.16	-31.8	.01
Horn Lake	0.88	0.97	+10.2	ns
Cecebe Lake	1.11	1.01	-9.0	ns
Etwell	1.66	1.15	-30.7	.01
Musquash River	nd	1.06	nc	nc
Point Ideal	1.00	1.01	+1.0	ns
Swan Lake	1.09	0.95	-12.8	.05
Utterson	1.04	1.03	-1.0	ns
Muskoka Mean	1.23	1.04	-15.4	.01
Indian River	1.27	0.88	-30.7	.01
Woodview	0.91	0.93	+2.2	ns
Peterborough Mean	1.09	0.90	-17.4	.01
Thunder Bay	1.13	1.11	-1.8	ns

% Difference - per cent difference in growth in the most recent 30 years (1955-1984) relative to the first 30 years of the century (1901-1930).
nd - no data, some trees less than 70 years old.
nc - not calculated.
ns - not significant, p>0.05

Table 35
Comparison of Long Term Growth Rates of Sugar Maple,
All Tree Condition Classes Combined:
Specific Volume Increment - Stem Analysis Data.

Study Site	Specific Volume Increment (mm) 1901-1930	1955-1984	% Difference	p<
Magnetawan	0.63	2.12	+236.5	.01
Horn Lake	1.22	1.84	+50.8	.01
Cecebe Lake	1.16	1.65	+42.2	.01
Etwell	1.07	1.16	+8.4	ns
Musquash River	nd	1.68	nc	nc
Point Ideal	1.60	1.04	-35.0	.01
Swan Lake	1.04	1.14	+9.6	ns
Muskoka Mean	1.13	1.52	+34.5	.01
Indian River	1.49	1.03	-30.9	.01
Woodview	2.14	0.73	-65.9	.01
Peterborough Mean	1.81	0.88	-51.4	.01
Thunder Bay	0.88	0.97	+10.2	ns

% Difference - per cent difference in growth in the last 30 years (1955-1984) relative to the first 30 years of the century (1901-1930).
nd - no data, some trees less than 70 years old.
nc - not calculated.
ns - not significant, p>0.05

greater confidence can be expressed in the results. In contrast, the entire tree must be sacrificed to obtain the data required to generate SVI, a practice that is costly in terms of time and environmental material, and that severely restricts the number of trees that can be sampled; therefore, the population is less representative and less confidence can be expressed in the results. However, SVI has been shown to be very responsive to environmental changes and may be a very powerful diagnostic tool. It could be that normalized increment core data may be more useful in identifying long term trends or evaluating regional responses and SVI is more responsive to short term or localized changes.

Regardless of the potential problems inherent with these two tree growth methodologies the MOE sugar maple decline etiology study had significant shortcomings that limited it's practical application for dendrochronological research of long term growth trends. Only mature dominant or co-dominant trees were selected, and many of these were chosen because of their decline symptoms. The sites were quite restricted geographically and the total number of trees sampled was small (increment cores = 44, SVI = 24). As part of a general program of forest decline research, the MOE initiated an extensive sugar maple dendrochronological study in 1986 and completed the field sampling in 1989. In this time period 69 sites were established across the sugar maple range in Ontario in stands with no visible decline symptoms. About 100 mature trees were destructively sampled for detailed stem analysis and about 1200 increment cores were collected from all trees on the plots greater than 10 cm dbh. The stem analysis data have not been fully prepared to date but examination of the increment core data is well under way. By combining trees of all ages (fast growing young trees with slower growing older trees) the issue of reduced ring width with time (which is a characteristic problem encountered when only mature trees are sampled) is, in theory, overcome. Similarly, with a large sample size, greater confidence can be expressed that the results are representative.

Table 36 summarizes the long term growth rates of sugar maple in relation to regional pollution levels in Ontario. The time periods for comparison are the same as previously described, i.e., the 30 years from 1901 to 1930 and 1955 to 1984. The three sets of data are the indexed ring values and SVI from the etiology study and the unfiltered ring widths from 1200 sugar maple sampled for the provincial dendrochronological study. The data are divided into three air pollution deposition zones, simply defined as high, moderate and low. The high zone is characterized by combined wet and dry SO_4 and NO_3 average annual deposition of about 51 kg/ha/yr, 7 hour daylight growing season O_3 concentrations averaging about 50 ppb, and mean annual precipitation pH of 4.2. The moderate zone is defined by total SO_4 and NO_3 deposition of 43 kg/ha/yr, O_3 concentrations (7 hour daylight growing season mean) of between 30 and 40 ppb, and average precipitation pH of about 4.2. The combined acidic deposition in the low zone is about 15 kg/ha/yr, less than 20 ppb O_3, with the precipitation averaging about pH 4.8.[64, 105] For both the indexed ring values and the SVI data obtained from the sugar maple decline etiology study, the high deposition zone includes both Peterborough study plots, the eight plots in the Muskoka area comprised the moderate zone, and the single Thunder Bay site is the low deposition zone. The unfiltered ring widths from the provincial dendrochronology study included sample plots from the Long Point, St. Williams, Peterborough, and Barrie areas in the high deposition zone. The moderate zone comprised plots from the Muskoka, Haliburton, Algonquin Park, Carleton Place and Ottawa areas. Plots between Sault Ste. Marie and west of Sudbury were included in the low deposition zone.

Table 36

Comparison of Long Term Growth Rates of Sugar Maple Relative to Regional Pollution Deposition, Using Three Tree Ring Interpretive Methodologies.

Methodology Deposition Zone*	Ring Width 1901-1930	1955-1984	% Difference	p<
Indexed Ring Values:				
High (n=8)	1.09	0.90	-17.4	.01
Moderate (n=32)	1.23	1.04	-15.4	.01
Low (n=4)	1.13	1.11	-1.8	ns
Specific Volume Increment:				
High (n=4)	1.81	0.88	-54.4	.01
Moderate (n=16)	1.13	1.52	+34.5	.01
Low (n=4)	0.88	0.97	+10.2	ns
Unfiltered Ring Widths at DBH:				
High (n=160)	1.92	1.40	-27.1	.01
Moderate (n=688)	1.10	1.03	-6.4	.05
Low (n=245)	0.78	1.09	+39.7	.01

% Difference - per cent difference in growth in the most recent 30 years (1955-1984) relative to the first 30 years of the century (1901-1930).
n - number of trees in sample.

* Deposition Rates - SO_4, NO_3, are total wet and dry kg/ha/yr mean from 1981 to 1984 after Tang et al (1986),[105] O_3 is 7 hr daylight mean (0900-1600 EST) June to August, mean 1974 to 1981 after Linzon et al (1984),[64] pH is mean from 1981 to 1984 after Tang et al (1986).[105]

Deposition Rates

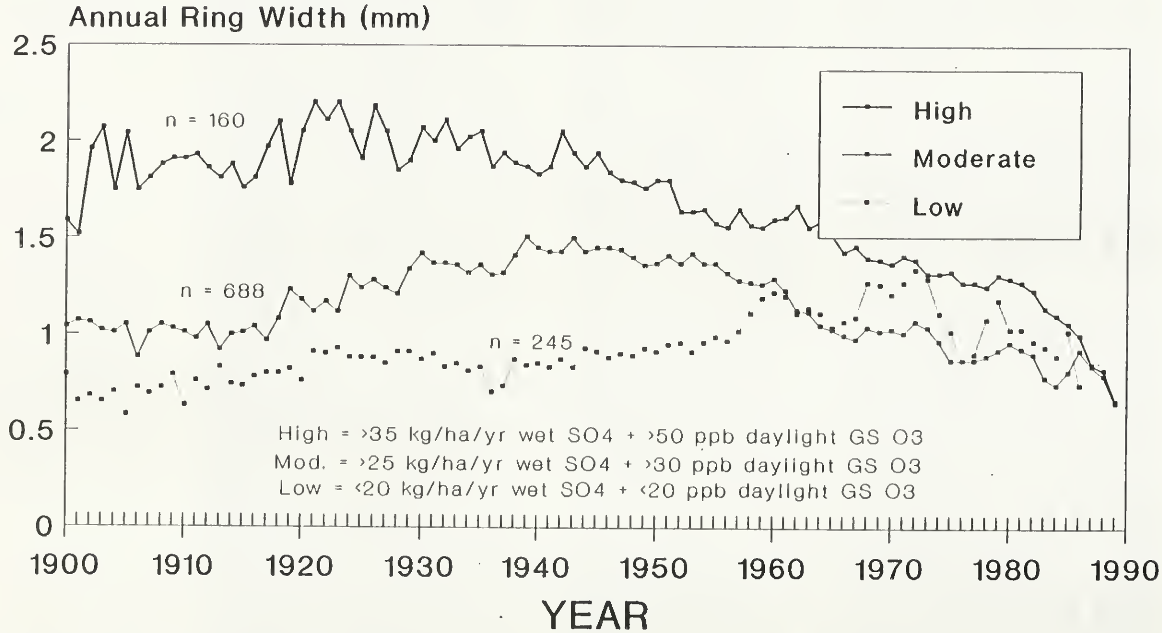
	SO_4	NO_3	O_3	pH
Low	12	3	<20	4.8
Moderate	34	9	40	4.2
High	43	8	50	4.2

Based on the largest sample from the greatest geographic area and combining all tree age groups, there has been a 27.1% ($p<0.01$) reduction in sugar maple annual incremental xylem growth in the last 30 years relative to the first 30 years of this century in trees located in the highest pollution deposition zone. In the moderate air pollution deposition zone, sugar maple growth has declined 6.4% ($p<0.01$) on average in the last 30 years. In the most northerly sample plots, where deposition is lowest, the sampled trees have had an average annual increase in incremental growth of 39.7% ($p<0.01$). These three growth chronologies are illustrated in Figure 36 and clearly show the trend towards consistent reduction in growth from about 1950 in the high pollution zone, about 1960 in the moderate zone, and a shift towards growth increase about 1960 in the low pollution zone. The growth trends of the unfiltered ring width data are consistent with the trends obtained by indexed ring values, and are similar to the SVI data, in that the most southerly plots located in the highest air pollution deposition zone had the greatest growth reduction and the northern plots from the lower pollution zones had the least growth reduction or had experienced a growth increase.

A simultaneous growth decline over a large area suggests a regional stress, such as climate or air pollution. The hardwood forest ecosystem can endure and recover from periods of natural stresses. However, regional air pollution such as acidic deposition and O_3, and the potential effect of pollution-related climate change, are new stresses that historically the forest has not been exposed to. In concurrence with periods of severe natural stress or during a period when natural stresses are uncharacteristically frequent, the compounding effect of the pollution stress would be to amplify the forest's physiological response. In this regard, regional air pollution can be considered as either a predisposing or contributing factor to forest decline. Simply stated, regional air pollution imposes a chronic stress, and so the forest's ability to rebound from periodic natural stress is impeded.

The determination of cause and effect dictates that a causal relationship can be inferred only when there is a strong pattern of consistency, responsiveness, and a proven biological mechanism with the suspected causal factors.[124] To conclude that the observed growth reductions are directly related to atmospheric pollutants is erroneous because this ignores the substantial climatic, biological, and other anthropogenic stresses that have occurred in the study regions during the same time period. Also, the physiological mechanisms linking forest decline and atmospheric pollutants, although anchored in sound theory, have not been proven. Considering the complexity of the tolerant hardwood forest ecosystem and the inter-relationships of the driving mechanisms, defendable proof (i.e., "hard evidence") of pollution-caused forest decline may never be obtained. However, the fact that sustained growth reductions have occurred concurrent with increasing atmospheric pollution levels, and that the reductions are greatest in areas of highest deposition, is circumstantial evidence of a link between forest decline and air pollution, and at least implies a predispositional or contributory causal relationship.

Sugar Maple Growth Across a Pollution Gradient In Ontario



Mean of all Trees >10 cm dbh

Figure 36
Sugar Maple Growth Chronologies from Three Pollution Zones in Ontario
(Average Ring Widths from Increment Cores).

9.10 Site Management

Proper woodlot management is critical if end-use objectives are to be realized. Sound silvicultural practices will improve individual tree vigour and increase overall woodlot productivity. Inadequately managed woodlots are not only less productive but the trees are less vigourous. Less vigourous trees are more susceptible to infection by secondary decay organisms and are damaged more easily by environmental stress. Therefore, woodlots that are inadequately managed may be predisposed to decline.

Management practices, history, and related stand characteristics of the 11 study sites were reviewed and scored to obtain a relative index of management status. The objective was to identify sites where management practices may be contributing to reduced tree vigour and therefore potentially predisposing the stand to decline.

Table 37 summarizes the scores obtained for each study site. The scoring is explained at the bottom of the table. The site total scores are listed adjacent to the mean site Decline Index in the two right columns. A low site score indicates a low frequency of the kind of stand characteristics and management practices that could contribute to decline, and therefore their absence should encourage tree vigour. In contrast, a higher score indicates that management practices and stand characteristics may be inhibiting tree vigour and possibly predisposing the woodlot to decline. Listed in order of increasing score (i.e., sites where management is least likely to adversely affect stand health to sites most likely affected) the study sites are; Swan Lake < Point Ideal = Cecebe Lake < Thunder Bay < Horn Lake < Musquash River = Utterson < Indian River < Etwell = Magnetawan < Woodview.

The relationship between mean Decline Index and the score derived from data in Table 37 is inconsistent. This inconsistency is not surprising because the etiology study has identified various causal agents. However, the score suggests that woodlot management for at least three sites (Woodview, Magnetawan and Etwell) has contributed to the observed decline.

Table 37
Stand Characteristics and Management Practices, a Weighting Scheme to Identify Sites Possibly Predisposed to Decline.

Study Plot	Trees Tapped	Site Class	% Sugar Maple	Woodlot Grazed	Age Class	Basal Area	Skid Trails	Recently Thinned	Total Score	Mean DI
Thunder Bay	0	1	1	0	2	0	0	0	4	13.5
Magnetawan	1	2	1	2	0	0	2	1	9	40.2
Horn Lake	1	0	2	0	1	0	1	0	5	17.7
Cecebe Lake	0	0	0	0	2	0	1	0	3	33.0
Etwell	1	1	2	1	0	2	1	1	9	28.2
Utterson	1	0	0	0	1	1	2	1	6	14.0
Musquash R.	0	1	0	0	1	2	1	1	6	24.0
Point Ideal	1	0	0	0	0	0	1	1	3	10.2
Swan Lake	0	1	0	0	1	0	0	0	2	18.4
Woodview	1	2	1	1	2	0	3	0	10	21.2
Indian R.	1	1	2	1	0	0	1	1	7	9.2

Scoring Explanation

Trees Tapped:	- trees in woodlot not tapped for maple syrup production = 0, trees tapped for maple syrup production = 1.
Site Class:	- MNR Site Class 1 = 0, MNR Site Class 2 = 1, MNR Site Class 3 = 2.
% Sugar Maple:	- <75% of the basal area in sugar maple = 0, >75% = 1, >90% = 2.
Woodlot Grazed:	- cattle have never grazed in woodlot = 0, historically grazed = 1, currently grazed = 2.
Age Class:	- all age classes present = 0, age class missing or >35% of the basal area in one age class = 1, missing age class and >35% of the basal area in one age class = 2.
Basal Area:	- >60 to <150 ft^2/ac = 0, <60 ft^2/ac = 1, >150 ft^2/ac = 2.
Skid Trails:	- none = 0, few = 1, many = 2, excessive = 3.
Recently Thinned:	- woodlot has not been thinned in the last 15 years = 0, has been thinned = 1.
Total Score:	- sum of the individual ratings, the higher the number the greater the stand characteristics and management practices have potentially contributed to tree decline.
Mean DI:	- mean Site Decline Index, 1984 to 1989.

10.0 Conclusions

The forest ecosystem is dynamic and surprisingly elastic. The forest's elasticity, which is primarily a function of diversity (both diversity of species and genetic diversity within species) is critical to it's perpetuity as an ecosystem. Elasticity enables the forest to rebound from short-term environmental stress. These short-term stresses, such as insect outbreaks and adverse climatic events, are intermittent and therefore impose a stress on the forest at periodic intervals. Providing the stresses are infrequent, any effect is temporary, and the forest usually recovers. The more frequent the stress, the less time the ecosystem has to recover, and the resultant effect is much greater.

Since 1971 there has been a climate stress event almost every year in Peterborough and virtually every other year in both Muskoka and Thunder Bay. This stress frequency is far greater than any other time in recorded weather history (the average climate stress frequency is about one in five to seven years) and has unquestionably adversely affected tree health in the study areas. In addition, the Muskoka area has experienced two major outbreaks of forest tent caterpillar during this period of frequent climate stress. The dendrochronological data clearly reveals that sites in Muskoka with the greatest severity and extent of tree decline in the mid 1980s were severely and repeatedly defoliated from 1976 to 1978.

It was concluded that the combination of climate and defoliation stress was the inciting factor of sugar maple decline in Muskoka. All Muskoka sites except Swan Lake were severely affected by the tent caterpillar epidemic of 1976 to 1978 (Swan Lake was only lightly impacted). In addition, symptomatic trees at Hom Lake and Musquash River recovered very slowly from tent caterpillar defoliation in the mid 1960s. Swan Lake was the least affected by tent caterpillar defoliation, although the site has been exposed to a relatively high level of Bruce spanworm activity.

Traditionally, defoliation has not been considered a major threat to forest health. However, when defoliation occurs concurrently with other environmental stresses the adverse effect is amplified because the system does not have the opportunity to recover from one stress before it is affected by another. Concurrent stresses may act cumulatively and/or synergistically. Under these circumstances, stored starch reserves and general tree vigour plummet. Consequently, the tree is much more susceptible to infection by secondary organisms that are able to act more virulently. Fungi such as *A. mellea* may contribute directly to tree mortality subsequent to defoliation or in a period of continuous environmental stress. This obscures the true cause of decline, as the tree may die as a result of *A. mellea* infection; but it was the combination of defoliation and climate stress that enabled the fungus to obtain a lethal stranglehold on the tree.

The inciting factors of sugar maple decline at Woodview, the one Peterborough site where significant decline was evident, were climate stress in combination with inefficient stand management, both of which were exacerbated by poor site conditions. Although climate stress also adversely affected the nearby Indian River study site, the superior site quality and more conscientious management regime limited the decline to older and therefore naturally more susceptible trees.

Climate stress was also concluded to be the inciting factor of the decline observed at Thunder Bay. A chronic forest tent caterpillar presence may have contributed to individual tree decline, but defoliation has not likely significantly inhibited overall stand vigour (Aspen is the preferred host in

the northern regions). The fact that sugar maple is at the extreme northern edge of it's range in Thunder Bay would make it particularly susceptible to adverse climate.

Table 38 summarizes the various *inciting, contributing* and *predisposing* factors that this study identified to be associated with sugar maple decline at the 11 study sites. Although climate and insect defoliation were concluded to be the inciting factors, it is clear that the decline observed in Ontario sugar maple in the mid 1980s was a complex, multi-factorial, site specific phenomenon. Phosphorous deficiency was likely a contributing factor at most of the Muskoka sites, whereas Zn deficiency possibly contributed to decline in both the Muskoka and Peterborough areas.

Sulphur deficiency may have been a contributing factor in Thunder Bay. The extreme northern location and the genetic specialization associated with this sugar maple ecotype limit it's adaptability. Because it is less flexible (i.e., the ecosystem is less elastic) it is more susceptible to stress. Therefore, location and limited genetic diversity could be considered as predisposing factors to sugar maple decline in Thunder Bay.

Based on the frequency of observation of fungal rhizomorphs and fruiting bodies, infection by *A. mellea* was a significant contributing factor to tree decline at Magnetawan, Horn Lake, Etwell, Point Ideal, Cecebe Lake and Woodview. It is not coincidental that these plots were also the most severely defoliated, thereby giving this fungus the opportunity to assume a more virulent role. Inefficient or inappropriate stand management directly contributed to decline at Magnetawan, Etwell and Woodview. Management likely played a predispositional role at Horn Lake, Utterson, Musquash River and possibly Indian River. Coarse-textured and/or shallow soil exacerbated the environmental stress and therefore predisposed trees to decline at Magnetawan, Etwell, Musquash River, Cecebe Lake and Woodview.

All of the Muskoka sites have soils that are rated as sensitive to acidification. This means that they have a limited ability to buffer the acidity deposited from atmospheric pollution and, with time, perhaps only decades on the most sensitive sites, the soil system reaches a point where nutrients are washed away faster then they can be replaced and nutrient deficiencies occur. Soil acidification is an ongoing process during which the level of plant-available Al gradually increases. This increases the potential for P/Al antagonism in the roots, which can create a P deficiency in the tree even though soil P levels may not be limiting (P/Al antagonism may be responsible for the apparent foliar P deficiency observed at most Muskoka sites). Elevated soil plant-available Al levels are potentially toxic to the fine root system and can interrupt energy allocation within the tree, forcing it to redirect carbohydrate reserves to repair damaged roots and produce replacement roots. In times of low environmental stress the tree has the necessary reserves to conduct root repair and maintenance; however, when environmental stress levels are high, as they have been in the last 10 to 15 years, the reserves are not available and tree vigour can be severely inhibited as a result of poor root condition.

Table 38
Summary of Causal Agents Associated with Sugar Maple Decline at the 11 Study Sites.

Site	Inciting Factors	Contributing Factors	Predisposing Factors
Magnetawan	-tent caterpillar defoliation in conjunction with climate stress.	-low soil Zn. -low foliar P, K. -low root P. -root P/Al antagonism. -*A. mellea*. -Stand management.	-stress from air pollution. -poor site. -coarse soil texture. -soil sensitive to acidification. -low tree starch reserves. -tapping. -shallow soil.
Horn Lake	-tent caterpillar defoliation in conjunction with climate stress.	-low soil Zn. -low foliar P, K. -low root P. -soil acidification (Al >20 ppm). -root P/Al antagonism. -*A. mellea*.	-stand management. -stress from air pollution. -genetics.
Etwell	-tent caterpillar defoliation in conjunction with climate stress.	-low soil Zn. -low foliar P, K. -low root P. -stand management. -*A. mellea*.	-stress from air pollution. -coarse soil texture. -soil sensitive to acidification. -tree age, genetics. -tapping. -shallow soil. -low tree starch reserves.
Point Ideal	-tent caterpillar defoliation in conjunction with climate stress.	-low soil Zn. -low foliar P, K. -low root P. -*A. mellea*.	-stress from air pollution. -soil sensitive to acidification. -tapping.
Utterson	-tent caterpillar defoliation in conjunction with climate stress.	-low soil Zn. -low foliar P, K. -low root P. -soil acidification (Al >20 ppm).	-stress from air pollution. -tree age. -tapping. -stand management.
Musquash River	-tent caterpillar defoliation in conjunction with climate stress.	-low soil Zn. -low foliar P, K. -low root P. -soil acidification (Al >20 ppm).	-coarse soil texture. -stress from air pollution. -stand management. -tree genetics.
Swan Lake	-climate stress in conjunction with defoliation by Bruce spanworm and tent caterpillar.	-low soil Zn. -low foliar P, K. -low root P.	-stress from air pollution. -soil sensitive to acidification. -tree age.
Cecebe Lake	-tent caterpillar defoliation in conjunction with climate stress.	-low soil Zn. -low foliar P, K. -low root P. -soil acidification (Al >20 ppm). -root P/Al antagonism. -*A. mellea*.	-stress from air pollution. -shallow soil.
Woodview	-climate stress.	-low foliar Ca, Zn. -low root Zn. -*A. mellea*. -stand management.	-shallow soil. -poor site. -tapping. -tree genetics. -stress from air pollution.
Indian River	-climate stress.	-low foliar Ca, Zn. -low root Zn.	-tree age, genetics. -tapping. -stand management. -stress from air pollution.
Thunder Bay	-climate stress in conjunction with moderate but chronic tent caterpillar presence.	-low soil Ca, N, P, Mn. -low foliar S. -low root S.	-northern location. -tree genetics.

Soil sensitivity was considered a predispositional factor to tree decline at Etwell, Point Ideal and Swan Lake. Because the average soil plant-available Al level was greater than 20 ppm, soil sensitivity was considered a contributing factor to tree decline at Horn Lake, Utterson, Musquash River, and Cecebe Lake. This is about one half the level at which subtle but measurable effects have been observed in MOE sugar maple bioassay experiments. In addition, the tissue chemical analysis at some Muskoka sites (most notably Magnetawan, Horn Lake, and Cecebe Lake) revealed potential P/Al antagonism.

The reduction in annual incremental tree growth observed at the Muskoka and Peterborough sites has been concurrent with and proportionate to regional air pollution levels (i.e, growth reduction is recent and it is greatest in areas of highest deposition). Reductions in tree growth in conjunction with soil sensitivity and indications at some sites of increasing soil acidity and P/Al antagonism, imply that air pollution cannot be ruled out as a stress factor. Through it's chronic presence, air pollution predisposes the forest to decline. If future research indicates that the current erratic climate, which is inciting tree decline across the province, is related to climate change through global warming, than the stress from air pollution would be regarded not as a predisposing factor but rather as a factor that contributes directly to forest decline.

The forest is an ecosystem in a state of dynamic equilibrium. It is in equilibrium because the forest continuously cycles minerals and biomass and will occupy a site in perpetuity. It is dynamic because it is constantly reacting to environmental influences and evolving through natural successional stages. The forest may change in appearance, tree species may gain or wain in relative abundance, but (barring major regional climate change) there will always be a forest. However, in the last 10 to 15 years the ecosystem has been stretched virtually to the limit of it's elasticity by an unprecedented frequency of stress events that has initiated and prolonged pockets of tree decline on sensitive sites. Although this recent series of natural stresses is unquestionably a rare event, statistically it has certainly occurred several times in the history of hardwood forest ecology in Ontario, and the forest has tenaciously survived. Because these previous decline episodes have gone largely unrecorded, our image of the current decline problem is therefore limited by a lack of historical perspective. Now, however, in addition to the numerous natural stresses, the forest also must endure the cumulative, and potentially synergistic, effects of the anthropogenic stress imposed by atmospheric pollutants. As the forest is already stretched to the limits of it's natural elasticity, this additional environmental stress warrants particular concern because it is impacting the forest ecosystem at a time when the tree's defence mechanisms and natural resistance are already at critically low levels.

11.0 Remedial Actions

There are no quick fixes for forest decline. The forest ecosystem, although dynamic, changes very slowly. If atmospheric pollutants are a factor contributing to forest decline in a specific region, then the prospects for an immediate solution are poor because the necessary emission reductions would be phased in over a protracted period of time, and ecosystem recovery would lag behind pollution abatement. Regardless of the specific causes of forest decline, woodlot owners are demanding information regarding remedial actions that they can employ now to either increase general tree health and perhaps prevent tree decline from occurring, or abate a current decline problem and hopefully initiate recovery.

The following suggested remedial actions are drawn from basic principles of forest dynamics, silviculture and tree physiology. They are intended for the management of sugar maple, and are offered with the understanding that woodlot recovery is not guaranteed. Tree decline due to mismanagement or acute climatic, biotic, or environmental stress may not respond to these remedial actions.

11.1 Site

Manage for maple on maple sites. This seems like an obvious principle, but just because maple is the dominant species on a particular site now does not necessarily mean that it is best suited for that site. Sugar maple may simply be the residual species remaining after a long history of harvesting. Management efforts for sugar maple should be concentrated on moderately deep, well drained, medium textured soil. These "fresh" sites are typically mid-slopes, plains or gently rolling upland plateaus. Excessively well drained hill tops and ridges, poorly drained valleys and shorelines, and very shallow soils should not be managed for sugar maple. A woodlot usually contains several site regimes. The various sites should be stratified by degree of management effort required to achieve specific objectives. Proactive management can then be concentrated on the best sites.

Sugar maple growth on good maple sites can be two or more times better than growth on poor sites. Vigorous trees are generally less susceptible to environmental stress and infection by secondary decay organisms.

11.2 Natural Associations

Sugar maple is naturally associated with yellow birch, basswood, red oak, black cherry, ironwood, white, green, and black ash, elm, soft maple and conifers such as eastern white pine, hemlock, white and red spruce and occasionally balsam fir. Natural tree associations may lessen the severity of species specific disease and insect infestations, more efficiently cycle nutrients, and provide more favourable regeneration conditions. Such sites also moderate microclimate and produce a woodlot with a greater potential commercial and recreational value and a better affinity for wildlife

attraction.

As a result of decades of selective species harvesting and single species management, it is not uncommon for sugar maple to compose 80% or more of stand basal area in northeastern tolerant hardwood forests. In addition, maple syrup producers have a practice of removing non-crop trees, therefore encouraging maple monocultures. It is preferable to develop a healthy forest and have to go farther from the sugar house to tap vigorous trees, then to have the convenience of close trees that may be less productive and perhaps predisposed to decline because of lower tree vigour. Also, a variety of tree species provides more diversified wildlife habitat and a wider potential market for forest products, and therefore a more flexible potential revenue for the woodlot owner.

11.3 Stand Age

All-aged stands provide a continuous recruitment of crop trees. Stocking and age class distribution should be manipulated to prevent complete canopy closure so that co-dominant and understorey trees are not suppressed. The stand should not become over-mature, even though these large trees are attractive as potential syrup producers. Crown closure dramatically reduces growth of understorey trees, saplings may stagnate or decline, and regeneration is inhibited. Suppressed trees are less vigorous and therefore more susceptible to decay and decline. Incremental growth (and therefore wood volume) of trees at all ages is significantly reduced in an over-mature forest.

11.4 Thinning

Periodic thinning, either for fuel wood or as part of a scheduled harvest, is a common practice in hardwood forest management. However, excessive or improperly timed thinning can incite decline in residual trees. Sugar maple is a shade tolerant tree species, which literally means it can survive in low light conditions. But the reverse is not true, in that it does not thrive under high light intensities. Sugar maple grows best under partial shading. Heavy thinning results in a radical increase in light intensity to the residual trees. This may result in increased incidence of sunscald, frost cracking, top decline, stem forking and epicormic sprouting. Injured areas on the tree are infection courts for decay organisms and may result in an inherent loss in tree vigour.

Thinning also increases the light level to the forest floor. High light levels increase soil temperature, which promotes evaporation and hastens soil moisture loss. A drier, warmer and better lit forest floor encourages the growth of ground vegetation and may discourage tree regeneration.

These problems seem to be particularly evident after thinning very low or very high basal area stands. As a conservative thinning guide, on poor sites thinning should not exceed 10% of the basal area per year. The percentage of the basal area that can be removed in any one thinning cut can be increased on better sites, where higher inherent tree vigour and more favourable soil characteristics enable the residual trees to cope with the higher light intensities, increased temperature and possible

reduced soil moisture. Good maple sites should be able to respond well to thinning cuts of 30% of the basal area. In a period of very low environmental stress these thinning values may be marginally increased. However, when environmental stress is acute or has been chronically present for several years, thinning should be reduced, or possibly even postponed until the stress on the forest ecosystem has abated.

What is the optimum residual basal area? Growth studies conducted by the MNR have determined that the maximum growth response of sugar maple occurs at about 14 m^2/ha (about 60 ft^2/ac). Furthermore, after 20 years, the trees have filled up the growing space and growth returns to pre-thinning levels. Therefore, a cutting cycle of about 20 years that thins the stand to about 14 m^2/ha maintains sugar maple at optimum vigour, as measured by incremental growth. Many stands in Ontario have basal areas considerably higher than 14 m^2/ha. With thinning regimes of between 10% and 30% of the basal area (depending on site quality and level of environmental stress) it may take several thinning cuts over several years to obtain the desired basal area.

11.4.1 Thinning and Insect Defoliation

Defoliation in the first half of the growing season destroys the photosynthetic base of the tree before the leaves have assimilated enough energy to replace the stored starch reserves utilized in the initial leaf production. Also, given favourable weather conditions, defoliated trees usually attempt to refoliate. This consumes even more of the stored starch reserves and leaves the tree perilously low on the energy necessary to fuel root growth and prepare for bud formation and winter dormancy. For these reasons, defoliation can frequently result in mortality, particularly on poor sites or when defoliation occurs concurrently with unfavourable weather conditions. Trees defoliated twice in one growing season, or severely defoliated in consecutive years, are particularly affected.

Therefore, thinning harvests should not be conducted before a pending outbreak of defoliating insects, because the thinning cut followed by possible insect-related mortality may result in a basal area reduction greater than the scheduled 10% to 30%, and so predispose the residual trees to decline. The annual Forest Insect and Disease Surveys conducted by Forestry Canada are a reliable information source of insect activity on a regional level and should be consulted before executing a thinning harvest.

The same logic can be applied regarding thinning during or immediately after a serious defoliating insect epidemic. Some delayed mortality may occur and additional thinning may run the risk of increasing the light intensity of the residual stand too much, resulting in decreased rather than increased tree vigour. However, dead trees should be removed. Salvage harvests can utilize the timber and at the same time remove potential infection courts that may reduce the frequency of some secondary decay organisms.

11.4.2 Thinning, Tree Genetics and Stand Improvement.

When conducting thinning harvests the temptation to market only the highest quality timber in the woodlot should be resisted. Many desirable tree characteristics, such as growth rate, form, resistance to disease, sap sweetness and sap volume, are genetically inherited traits. By harvesting the best, the poorer trees are left by default. The residual trees, in turn, may form the major component of the future growing stock. Therefore, "high grading" as the practice is called, can result in decreased residual tree quality and may reduce the genetic potential of the stand. It is, in fact, the poorest quality trees that should be removed (in a stand improvement cut) to stimulate growth of the superior growing stock and improve the potential of the residual stand.

11.4.3 Individual Tree Removal.

Tree removal, other than planned (and properly timed) thinning, should be avoided. This is more of a concern for maple syrup producers, most of whom remove individual unthrifty or declining trees annually to fulfil their constant requirement for fuel wood. Trees with decline symptoms should not be removed until they are dead. The most obvious reason is because recovery of declining trees has frequently been documented, and premature removal may eliminate an established crop tree. Another reason for delayed tree removal is to prevent radical light intensity changes to the crowns of adjacent co-dominant healthy trees. If a declining tree does not recover, it usually takes several growing seasons before the entire crown is dead. This progressive crown deterioration provides a gradual change in the canopy light level to adjacent trees, thereby minimizing light shock and the possible associated decline problems. Following a similar logic, avoid removing trees in pockets or groups. The resultant island of full sunlight may result in crown dieback in the adjacent edge trees. Also, sugar maple regeneration requires partial shade; full sunlight on the forest floor will encourage the establishment of other tree species or cause a proliferation of ground vegetation that may strangle tree seedlings.

11.4.4 Thinning, Disturbance and Cut Control

Although main anchor roots may penetrate the soil to several metres, depending on soil texture and depth, the small fine feeder roots that supply the tree with virtually all it's nutrients and moisture, are much shallower, usually less than 30 cm and sometimes proliferate in the soil organic layer. Damage to the fine feeder roots imposes an immediate and direct loss of tree vigour. Therefore, all woodlot activities should be conducted in a manner that minimizes soil disturbance in order to avoid root damage. This is particularly critical in the spring when the ground is soft and the roots are actively growing, on shallow sites where the roots may be closer to the surface, and in times of environmental stress when the tree vigour is inherently inhibited.

The following cut control guidelines are suggested to minimize site disturbance. They should be followed as a matter of habit as part of a good forest management regime, but they become critical in times of environmental stress.

- winter is the best time for harvest, as the frozen ground protects the soil, and snow cover provides some protection to regeneration.

- logging should not be conducted in the spring or in wet weather, when soil is soft and disturbance is greatest. Also, in the spring the bark is very loose due to cambial activity and the trees are very susceptible to mechanical damage.

- use the smallest practical machinery to skid in the bush. Rubber tracked vehicles may be preferable on wet and poor sites.

- minimize skid trails, and therefore minimize site disturbance. Use existing trails where possible, plan new trails in advance of the cut, keep them as short, straight, widely-spaced and as few as possible, with gentle curves and easy grades. The angle of trail intersections should be small (i.e., 30° max.).

- locate trails close to trees marked for removal, and use these trees as "bumper" or "rub" trees. Similarly "swing" or "pivot" trees at trail turns and intersections also should be trees planned for removal.

- to avoid detours around slash, start the harvest at the back of the cut and work towards the trails.

- use directional felling. Fell the trees such that the tops are away from the skid trail to avoid swing damage (i.e., 20° to 30° to the axis of the trail).

Site disturbance is an inevitable consequence of tree harvesting. However, by practising cut control the damage to the residual trees will be minimized. Scheduled thinning is necessary in order to achieve long-term woodlot management objectives. But the primary long-term objective should be to maintain the forest in as healthy and as vigorous a state as possible. This implies that scheduled thinning may have to be modified in times of environmental stress. When growing conditions are poor, harvest more conservatively and practice strict cut control. In periods of very severe environmental stress it may be advisable to postpone a planned harvest until conditions improve.

There are consequences to cutting more conservatively. Long-term objectives will take longer to achieve. It may promote slower growth and therefore less productivity. It may bias against less-tolerant tree species. It may retain higher cull levels. Depending on the objectives, wildlife habitat may suffer. However, the corollary to a more conservative thinning regime is that in times of environmental stress, a modified cutting regime will lessen the impact on the forest ecosystem and therefore reduce the likelihood of precipitating or contributing to tree decline.

11.5 Access.

Although it is an old adage, it cannot be repeated often enough. Cows make poor foresters and woodlots make poor pastures. Grazing cows trample, uproot and eat regeneration. The soil becomes compacted, which further impedes seedling establishment and inhibits percolation of moisture into the rooting zone. Sharp hooves damage the root collar of larger trees, thereby exposing the tree to direct infection by decay organisms. It takes from 2 to 10 ha (5 to 25 ac) of woodland pasture to provide the nutrient equivalent of 1/2 ha (just more than 1 ac) of improved pasture. In addition, because woodland pasture has a lower inherent nutrient status, cows grazed in the bush produce less milk and beef. Despite these well known relationships, a recent survey of maple syrup producers in Ontario revealed that 32% of the respondents had grazed their woodlots in the last 10 years.

11.6 Sanitation.

Keeping the bush clean helps to keep it healthy. Remove felled trees from the bush and pile the wood in a central location. Watch for bark beetles, as these can be a vector for other decay organisms that may infect standing timber. An insecticide application to the wood pile may be required, a maintenance procedure made much easier if the timber has been skidded and piled in a central location. Cankered trees are always candidates for removal when selecting trees for thinning. Cankered wood or wood with fruiting bodies should not be stockpiled. This material should be burned to inhibit disease spread.

11.7 Maple Syrup Production, Some Special Considerations.

Tapping a tree is an additional stress. How much of a stress, however, is difficult to quantify. Estimates vary widely, but it is possible that tapping removes between 5% and 10% of the sap volume, although this may be only 1% to 3% of the trees's total energy reserves. Each tap hole destroys a portion of the sapwood near the tapping wound. After the tapping season, the affected section of the sapwood will never again conduct sap or store the trees's energy reserves. It is dead wood. Healthy trees quickly and effectively "wall off" the wound area around the tap hole to prevent invading fungi from gaining access to the interior sapwood and possibly spreading within the tree. Less thrifty trees have less efficient defence mechanisms and the resultant wound area may be much larger than the area immediately around the tap hole. A tree under stress will utilize all of it's energy to maintain shoot and root growth and may have nothing left for defense and wound repair. Therefore, trees that develop advanced decline symptoms should not be tapped.

Consider a reduced tapping rule, possibly as low as two taps per tree regardless of tree size. A dramatically reduced tapping rule may make some operations uneconomical, even with the current high market prices for syrup. If more taps are required, tap more trees rather than installing more taps per tree. Do not cluster the tap holes. Tap in a helical pattern around the tree so that there is less likelihood of tapping dry wood in subsequent seasons or causing the internal wounds to coalesce

and girdle the tree. Clustered tapholes are more of a problem with tube operations. This tendency can be overcome by increasing the length of the drop line.

Since tapping is an additional stress, syrup producers should consider not tapping, or substantially reducing their tapping effort, in a year when the trees are or will be experiencing other significant environmental stresses. These would include springs following exceptionally cold winters in which there was little insulating snow cover, seasons following a severe drought or insect defoliation, or the year when, according to government survey forecasts, a severe insect epidemic is predicted. It is better to forfeit a season's profit than invest the necessary resources and obtain a very marginal return. Even worse, it could impose an additional stress on an already over-stressed ecosystem and possibly contribute to or exacerbate a decline situation.

A clean drill bit and spile should be used for every tap hole. Disinfect the bit between holes to eliminate the spread of disease between trees. Disinfection can be achieved quickly and easily by dipping the bit and spile in 95% denatured alcohol or a 1:5 Javex:water solution. Drill the tap hole on a very slight upward angle so that drainage is out of rather than into the hole. This lessens the likelihood of decay fungi becoming established.

The use of paraformaldehyde tablets is strongly discouraged. Paraformaldehyde increases sap yield because it inhibits the tree's natural healing process. Paraformaldehyde kills the wood immediately adjacent to the tap hole and significantly inhibits callous formation. Tapholes treated with paraformaldehyde take considerably longer to heal and therefore the wound is exposed to infection for an extended time period. Experiments have shown that untreated tap holes create a vertical wound in the sapwood with an average length of 4.9 cm. The average wound length in paraformaldehyde-treated tap holes is 19.8 cm.

There is another aspect of paraformaldehyde use not related to tree health. Maple syrup is marketed as an all-natural, pure food product; a concept that has considerable appeal with today's consumers. The use of paraformaldehyde tablets results in paraformaldehyde residue in the sap and a few studies have detected it in the final product. The presence of paraformaldehyde in maple syrup may jeopardize the purity status and corrupt an important and effective marketing strategy.

Tapping with tubing has obvious advantages over traditional sap collection by bucket. However, there are additional factors that make tubing the preferred method. There is a greater economy of scale with tubing. It is considerably less expensive per tap to increase the number of taps. But, don't increase the number of taps per tree; rather increase the number of trees tapped. Tube collection does not require frequent trips to the bush to empty buckets, a considerable labour savings, but more importantly there is much less walking and driving around in the bush in the early spring and so less potential for root damage as a result surface soil disturbance.

11.8 Fertilization and Liming.

Will fertilization or liming prevent or limit the severity of hardwood forest decline, or initiate recovery in a bush that is currently experiencing decline? Some success has been achieved in reducing decline symptoms in studies in Quebec and Europe. A popular theory on the cause of forest decline is that the forest soils are being leached of essential nutrients by atmospheric pollutants faster than they can be replaced by the forest/soil ecosystem, thereby initiating nutritional stress or even deficiencies. Even if changes in soil fertility are not directly related to air pollution or tree decline, an increase in tree vigour may be achieved on some sites through fertilization, particularly where nutrient levels are less than optimal. Healthy, vigorously growing trees are better able to withstand environmental stress.

Fertilizer applications must be made with reference to soil pH and in balanced combinations to avoid possible adverse effects on tree health. For example, acidic soils may increase the availability of nutrients already in mineral form but the microbial activity necessary to decompose forest litter is usually inhibited by low pH, thereby slowing the rate of forest nutrient cycling. In addition, acidic soils stimulate metal availability, such as Al, which can damage roots and interfere with nutrient uptake. Adding lime to raise soil pH will stimulate soil microbial populations and litter decomposition and reduce Al availability, but the relative availability of mineral nutrients will also be lowered. Therefore, if lime is to be added to raise soil pH, then additional mineral fertilizers also must be added with the lime to boost nutrient levels.

Trees tend to take up what they can, not necessarily what they need. Too much lime or fertilizer may be damaging. For example, too much N has been shown to delay cold weather hardiness and therefore increases the risk of frost damage in the fall. Similarly, too much lime not only decreases the availability of macronutrients but also inhibits mycorrhizae on tree roots, which may lead to decreased uptake of the micronutrients B and Mn. Therefore, in addition to the macronutrients N, P, K, Ca, and Mg, the micronutrients B and Mn may be a requirement in the fertilizer mix whenever lime is applied.

Lime and fertilizer applications should be done in the spring as soon as the ground is free of snow, or in the fall if spring conditions are not favourable. Avoid mid/late summer applications because of potential problems with late season growth and fall hardiness. Moisture is critical; avoid applications at any time if the ground is too wet or too dry. Lime can be $CaCO_3$ or dolomitic lime but not calcium hydroxide (it is too caustic). Lime application rates should not exceed 400 kg/ha. Fertilizer trials in Quebec have met with encouraging preliminary results using N at 200 kg/ha, P_2O_5 at 100 kg/ha, K_2O at 200 kg/ha and Mg at 100 kg/ha plus lime. Researchers at MacDonald College of McGill University have met with favourable results in trials using the commercial fertilizer mixture CANAGRO W 4-4-8 plus lime and Mg. The application costs for these trials varied from $240 to $356/ha.

Fertilization of hardwood forests to increase fibre yield is generally considered uneconomical (i.e., the value of additional wood volume produced is less than the cost of fertilization). Similarly, regular fertilization of sugar bushes would be impractical because the treatment cost may exceed the revenue from syrup production. For example, based on the 1985 mail survey of Ontario maple syrup producers, the average sugar bush size was 24.8 ha and produced 829 litres of maple syrup that

sold (in 1985) for $8.29 per litre. This is an average gross return to the producer of $274.10/ha. Syrup prices have risen dramatically in the last few years, which should substantial improve the average gross return. The net return, however, is much lower if fuel, packaging and labour costs are considered.

If the decision to fertilize were made solely on economic principles, there would be no justification for regular fertilization. Fertilization may be considered even though it may not be cost effective, to improve tree vigour and therefore carry the stand through a period of environmental stress.

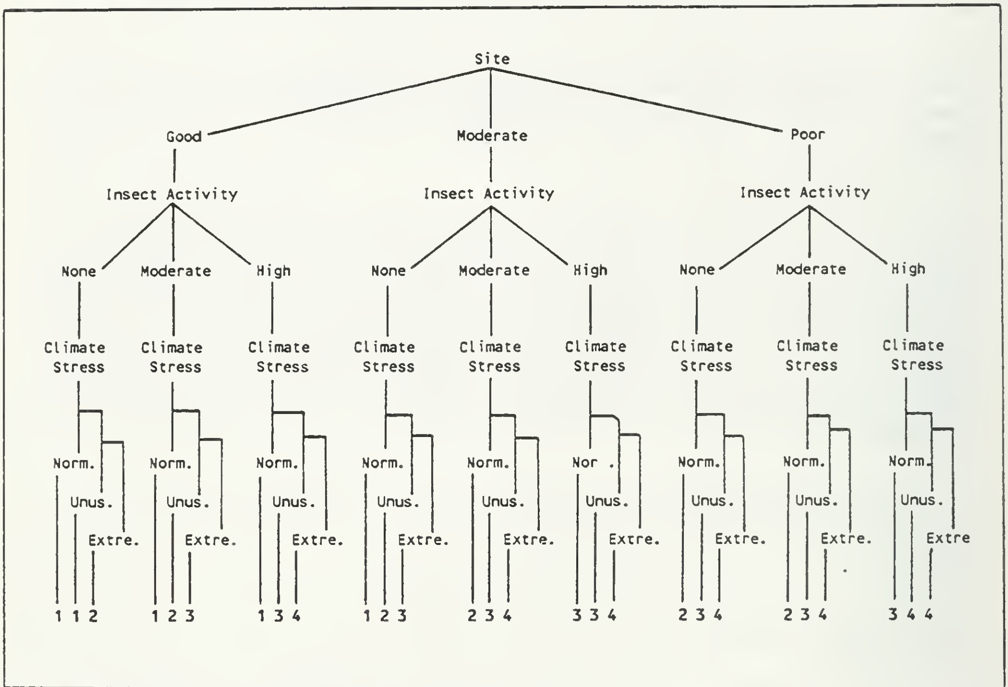
Woodlot fertilization is a significant cost to the owner, and although it has shown promise in recent trials, the results are not certain on all sites, and so a fertilizer program should not be conducted blindly. Knowledge of soil and foliar chemistry for the woodlot is necessary for an effective fertilizer program. Site specific chemical information is often difficult or costly to obtain and reliable data depends on the collection of representative samples. A simpler approach would be to establish fertilizer and/or lime trial plots in the woodlot to determine what appears to work best for a specific site. This is more time consuming and requires several seasons of careful treatment and observation; however, it will yield results that should indicate the best combination for an individual woodlot and may prevent a significant expenditure on a general fertilizer that may not work as well.

Like any other management tool, fertilization should be conducted on the sites that will respond best. Be selective.

11.9 Decision Guidelines.

Attached are two charts that have been developed as a management guide for woodlot owners. They are intended to assist in the identification of the level of environmental stress as it may relate to site quality, and suggest a corresponding degree of management effort. They are not complete. The final decision as to what level of activity is right for which site and at what time must still be made by the owner based on their knowledge and experience in their own woodlot.

Table 39
A Stress Detection Critical Pathway, a Guide for Woodlot Tapping and Thinning.



1 = low stress, thinning/tapping can be conducted as planned.
2 = moderate stress, slight modification of planned activity, thin/tap conservatively.
3 = high stress, significant modification of planned activity, thin/tap very conservatively.
4 = very high stress, cancel planned activity, postpone thinning/tapping until low stress season.

Good Site: deep soil (no rock outcrops), loamy soil texture prevents excessive drainage/waterlogging, gentle slopes.
Moderate Site: medium soil depth (few rock outcrops), sandy loam or clay loam infrequently results in dry/saturated conditions, medium slopes, not usually hill tops or wet valley bottoms.
Poor Site: shallow soil (rock outcrops abundant), coarse or heavy textured soil results in frequent periods of excessively dry or saturated conditions, commonly hill tops, steep slopes, or wet valley bottoms.

Insect Activity: usually refers to defoliating insects such as tent caterpillar, saddle prominent, bruce spanworm, gypsy moth (moderate stress would be 50% defoliation in the first and less than 50% defoliation in second and third year of cycle, high stress would be greater than 75% defoliation in the first year and greater than 50% defoliation in the second and third years, or a double defoliation in any one year.

Climate Stress: Norm = normal climate patterns for the entire year.
Unus = unusual climate in any part of the year, such as cool late spring/early fall, mild drought, warmer/colder than normal winter, low snowfall, etc.
Extre = extreme climate in any part of the year, such as unusually cold winter in combination with very low snowfall, high winter temperatures with thaw and sap flow followed by deep freeze, severe spring/fall frost, severe drought, prolonged very high summer temperatures, etc.

Table 40
A Decision Matrix for Woodlot Management.

Site	Good			Moderate			Poor		
Insect Stress	None	Moderate	High	None	Moderate	High	None	Moderate	High
Climate Stress	N U E	N U E	N U E	N U E	N U E	N U E	N U E	N U E	N U E
Business Factors									
Fertilize	0 0 0	M M 0	ok M 0	M M 0	M M 0	ok M 0	M ok 0	ok ok 0	ok M 0
Thinning	ok ok M	ok M 0	M M 0	ok M 0	M M 0	0 0 0	M M 0	M 0 0	0 0 0
Tapping	ok ok M	ok M 0	0 0 0	ok M 0	M M 0	0 0 0	M M 0	M 0 0	0 0 0
Plant/Seed	ok ok M	ok M 0	ok M 0	ok ok 0	ok M 0	M 0 0	ok M 0	M 0 0	0 0 0
Browse	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0

· Matrix Symbols:
ok = management can practised as scheduled.
M = management should be conservatively modified to lessen the potential site impact.
0 = management should be postponed or cancelled.

Site Guidelines:
Good Site - deep soil (no rock outcrops), loamy soil texture prevents excessive drainage /waterlogging, gentle slopes.

Moderate Site - medium soil depth (few rock outcrops), sandy loam or clay loam soil texture infrequently results in dry/saturated conditions, medium slopes, not usually hill tops or wet valley bottoms.

Poor Site - shallow soil (rock outcrops abundant), coarse or heavy textured soil results in frequent periods of excessively dry or saturated conditions, commonly hill tops, steep slopes, or wet valley bottoms.

Insect Stress: usually refers to defoliating insects such as tent caterpillar, saddle prominent, bruce spanworm, gypsy moth (moderate stress would be 50% defoliation in the first year and less than 50% defoliation in second or third year of cycle, high stress would be greater than 75% defoliation in the first year and greater than 50% defoliation in subsequent years, or a double defoliation in any one year).

Climate Stress: N = normal climate patterns for the entire year.
U = unusual climate in any part of the year, such as cool late spring/early fall, mild drought, warmer/colder than normal winter, low snowfall etc.
E = extreme climate in any time of the year, such as unusually cold winter in combination with very low snowfall, severe spring/fall frost, severe drought, very high summer temperatures, periods of high winter temperatures with thaw and sap flow followed by deep freeze, etc.

Plant/Seed - refers to woodland sites, not necessarily to open areas.

12.0 Related Projects and Future Directives

Although the sugar maple decline etiology study has been concluded, through agreements with the woodlot owners, the study plots may be maintained to monitor the tree decline status on a periodic basis. In addition to the etiology study the MOE initiated a series of projects to examine the relationship between tree decline, atmospheric pollutants and the terrestrial ecosystem. These projects include:

1. Biogeochemistry - 1982 to 1986, chemically characterizing ambient precipitation relative to forest throughfall, stemflow and soil in different forest stands across a pollution deposition gradient. Soil leachate studies are continuing at two sites in the Dorset and Huntsville areas.

2. Hardwood Forest Health Survey - 1985/86, established a network of 110 permanent observation plots in the hardwood forest zone of Ontario to monitor the change in forest health. The plots have been annually (except for 1988) since 1986.

3. Sugar Maple Dendrochronology Study - 1986 to 1989, collected tree ring records from over 1500 trees across the sugar maple range in Ontario to assess growth trends in relation to climate and pollution loadings.

4. Soil Sensitivity Mapping - 1983 to 1988, joint project with Environment Canada to prepare a map of Ontario identifying soil sensitivity to acidic precipitation in relation to the effect on aquatic acidity.

5. Soil Baseline Study - 1980/81, established 300 soil pits across the province to provide a soil chemistry data base against which future data could be compared to determine changes in soil acidity. About 100 of the pits were resampled in 1987.

6. Tree Foliage Chemistry - 1986 to 1989, established a foliar chemistry data base for sugar maple and yellow birch for a range of soil and site conditions.

7. Sugar Maple Sap Chemistry - initiated in 1986 (ongoing), this study has examined inorganic and organic constituents in sugar maple sap in relation to tree decline status.

8. Drought/Aluminum Interactions - 1985 to 1988, to examine the relationship between Al uptake and drought in sugar maple.

9. Nematodes - 1987, to characterize the number and species of nematodes in relation to tree decline status.

10. Mycoplasma-like Organism (MLO) - 1987, to determine if MLOs were causal factors in sugar maple decline in Ontario.

11. Simulated Acid Rain (SAR) Experiments - 1986 to 1989, SAR was applied to sugar maple and white spruce seedlings in outdoor exclusion canopies.

12. Remote Sensing - 1987, 1988 and 1991, field experiments were conducted to determine if selected aircraft-borne remote sensing technology could identify and characterize hardwood forest decline symptomatology.

13. Fertilization Trials - 1988 and 1989, established selected sites in the Dorset and Peterborough areas to determine if fertilization can ameliorate sugar maple decline.

14. Mycorrhizae - 1988 (ongoing), to characterize the species and abundance of mycorrhizal infection of sugar maple relative to tree decline status.

15. Wawa White Birch Decline - 1988 (ongoing), to examine the etiology of declining white birch south of Wawa Ontario.

16. SAR/Tent Caterpillar Interactions - 1988 to 1990, to examine the relationship between the growth, development and feeding patterns of forest tent caterpillar and sugar maple seedlings treated with SAR.

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